UNIVERSITÀ DEGLI STUDI
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Impact of small-x resummation on HERA data: new QCD results

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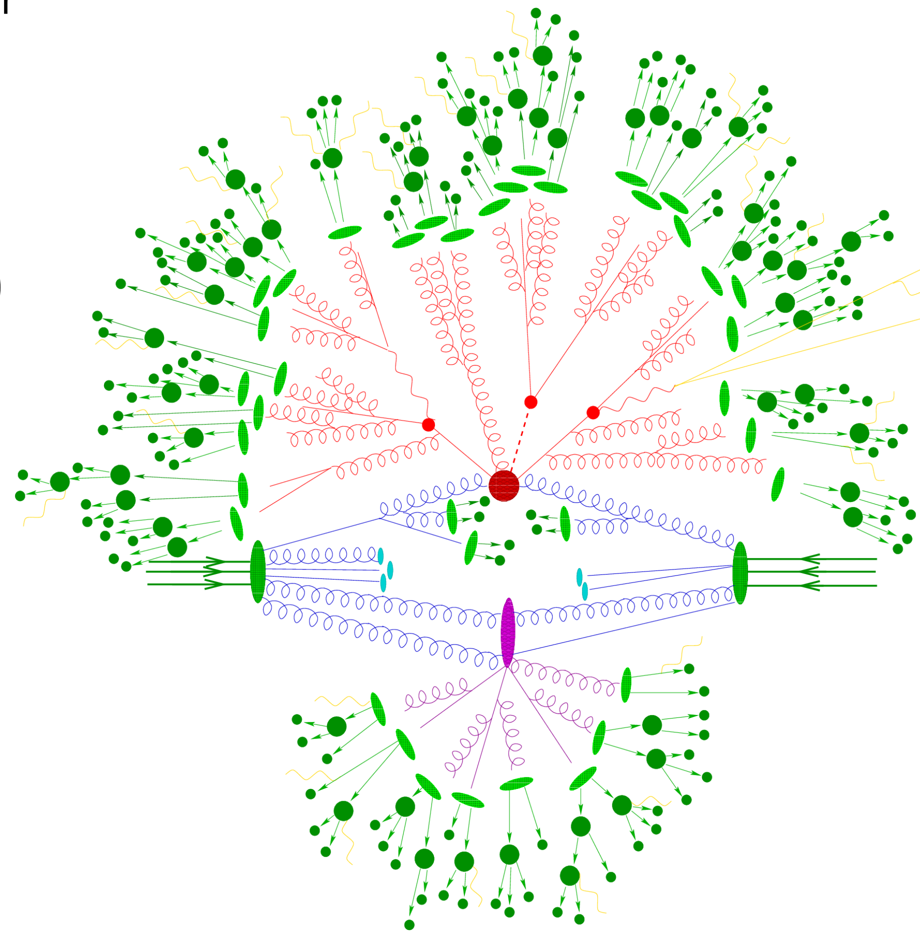
xFitter

Motivation

- No new physics found at the LHC so far
- Need for precise measurement of SM processes
- This means accurate higher order (HO) calculations…
- … but also precise knowledge of Parton Distribution Functions (PDFs)
- Proton-proton collision at the LHC
- For simplicity, let's consider Deep Inelastic Scattering (DIS) process
- Just one incoming parton



Factorisation theorem

$$\sigma_{DIS}(x, Q^2) = \int_x^1 \frac{dz}{z} C_i(z, \alpha_S(Q^2)) f_i\left(\frac{x}{z}, Q^2\right) = C_i \otimes f_i$$

Partonic cross sections:
- Process dependent
- High-scale (short-distance) objects
- Computable in perturbation theory (LO, NLO, NNLO, N^3LO)

PDFs:
- Universal (process independent)
- Low-scale (long-distance) objects
- Non computable in perturbation theory
- Scale dependence perturbative (DGLAP)

➢ Once PDFs have been **determined at a given scale**, the **DGLAP** evolution equations can be used to **evolve them to any other scale**

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(\mu) = P_{ij} \otimes f_j(\mu)$$

$$P_{ij}(y) = \frac{\alpha_S(\mu)}{2\pi} P_{ij}^{(0)}(y) + \left(\frac{\alpha_S(\mu)}{2\pi}\right)^2 P_{ij}^{(1)}(y) + \ldots$$

Splitting functions

How do we determine PDFs?

➢ Presently, the most accurate and reliable way is through **fits to data**

$f_i(x, Q_0^2)$

$x = p_i/p_p$
$0 < x < 1$
$Q_0 \sim 1$ GeV
(initial scale)

DGLAP →

$f_i(x, Q^2)$

Q = scale of the fitted data

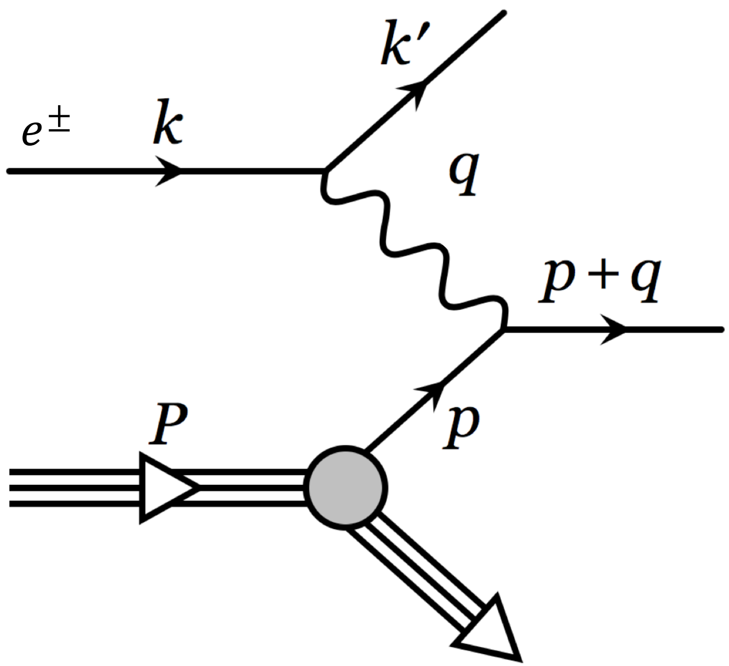
Factorisation theorem ↓

$\sigma_{DIS} = C_i \otimes f_i$

Fitting ↓

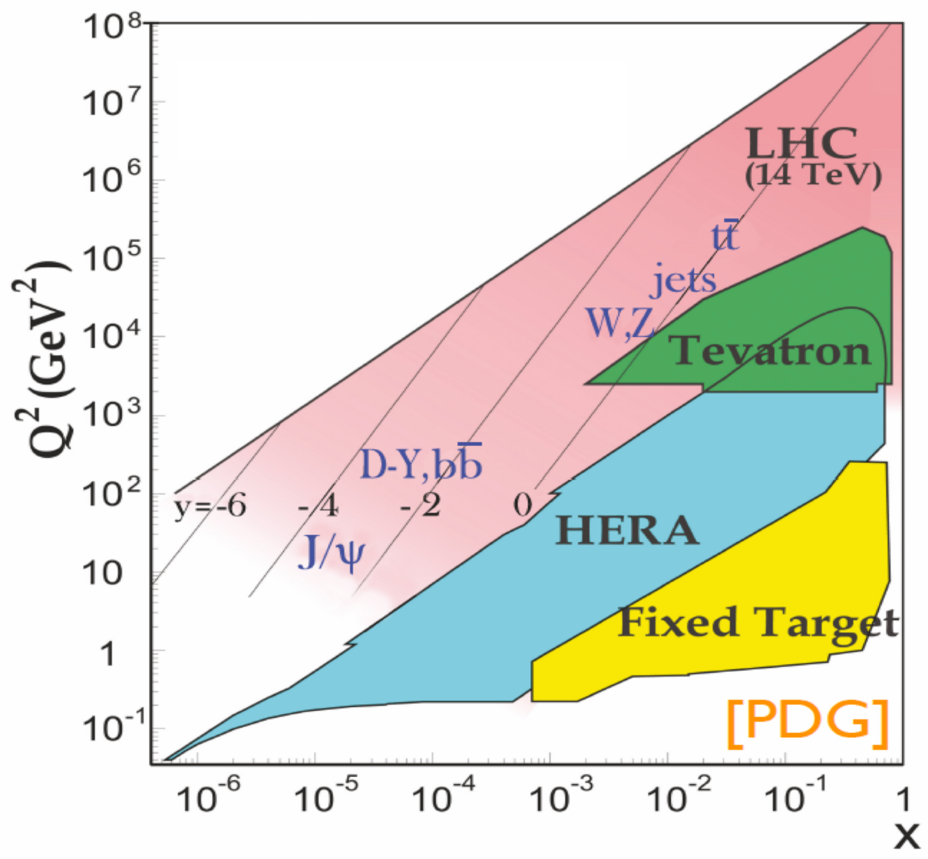
Predictions vs data

Deep Inelastic Scattering (DIS)



Anyway NOT an easy task

- **Datasets**:
  - as large and varied as possible
  - spanning a wide kinematic range
- Estimate of the **uncertainties**:
  - correlation of exp. uncertainties
  - various alternative procedures
- Choice of the **parametrisation**:
  - avoid parametrisation biases
- **Theoretical inputs**:
  - Higher order (HO) corrections
  - Heavy-quarks mass effect
  - …



Different choices my lead to different results

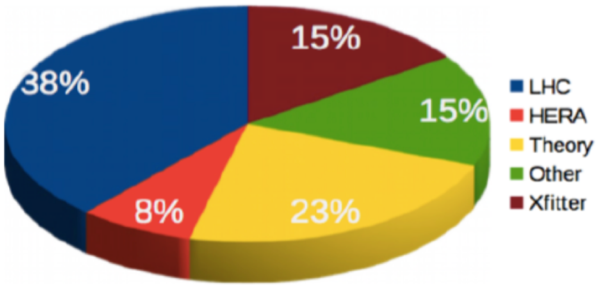
Available PDF sets on the market

- Several groups working on PDFs and different sets available on the market
  - CTEQ-TEA – CT14 – **private code**
    https://arxiv.org/abs/1506.07443
  - MMHT – MMHT14 – **private code**
    https://arxiv.org/abs/1610.04393
  - NNPDF – NNPDF31 – **private code**
    https://arxiv.org/abs/1706.00428
  - ABM – ABMP16 – **private code**
    https://arxiv.org/abs/1609.03327
  - JR – JR14 – **private code**
    https://arxiv.org/abs/1403.1852
  - CTEQ-JLAB – CJ15 – **private code**
    https://arxiv.org/abs/1602.03154
  - ....
  - xFitter – HERAPDF20 – **PUBLIC CODE**
    https://arxiv.org/abs/1506.06042

All the various PDF sets differ from each other because of:
- Theoretical setup
- Input parameters
- Datasets in the fit
- PDF parametrization
- ...

The xFitter Project

- The xFitter project (former HERAFitter) is a **unique open-source QCD fit framework**
- https://gitlab.cern.ch/fitters/xfitter (open access to download for everyone – read only)
- This code allows users to:
  - **extract PDFs** from a large variety of experimental data
  - assess the **impact** of **new data on PDFs**
  - check the **consistency** of experimental data
  - test different **theoretical assumptions**



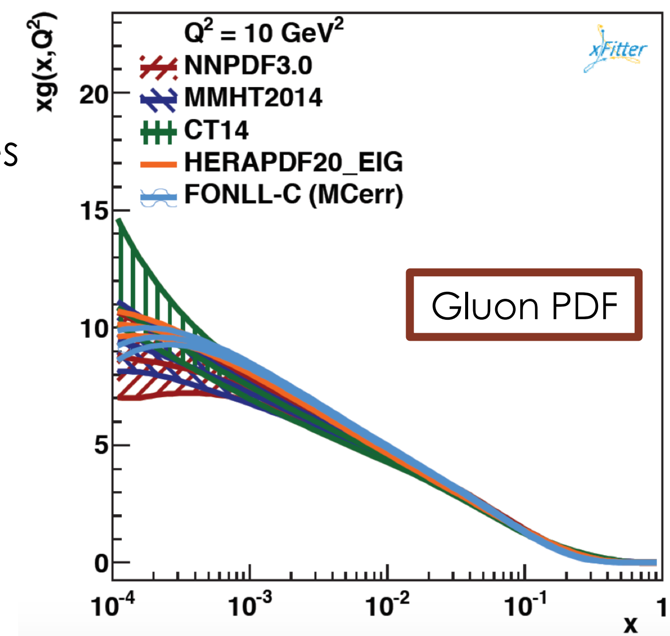
- Several active developers between experimentalists and theorists
- More than **80 publications** obtained using xFitter since the beginning of the project: https://www.xfitter.org/xFitter/xFitter/results
- List of recent analyses by the xFitter Developers' Team:

MORE IN PREPARATION!

7	02.2018	xFitter Developers and Marco Bonvini	Eur.Phys.J. C78 (2018) no.8, 621, arXiv:1802.00064	Impact of low-x resummation on QCD analysis of HERA data
6	07.2017	xFitter Developers	Eur.Phys.J. C77 (2017) no.12 837, arXiv:1707.05343	Impact of the heavy quark matching scales in PDF fits
5	01.2017	F. Giuli, xFitter Developers' team and M. Lisovyi	Eur.Phys.J. C77 (2017) no.6 400, arXiv:1701.08553	The photon PDF from high-mass Drell Yan data at the LHC
4	03.2016	xFitter and APFEL teams and A. Geiser	JHEP 1608 (2016) 050, arXiv:1605.01946	A determination of mc(mc) from HERA data using a matched heavy flavor scheme

xFitter in a nutshell

- **Parametrise** PDFs at the initial scale:
  - several functional forms available (more later)
  - define PDF parameters to be minimised
- **Evolve** PDFs to the scales of the fitted data points:
  - DGLAP evolution up to NNLO in QCD and NLO QED (QCDNUM, APFEL, MELA)
  - non-DGLAP evolutions (dipole, CCFM)
- **Compute** predictions for the data points:
  - several mass schemes available in DIS (ZM-VFNS, ACOT, FONLL, TR, FFNS)
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO)
- **Comparison data-predictions** via χ^2:
  - multiple definitions available
  - consistent treatment of the systematic uncertainties
- **Minimise** the χ^2 w.r.t. the fitted parameters
  - using MINUIT or by Bayesian reweighting
- **Useful drawing tools** – nice and colorful plots



xFitter release 2.0.0

xFitter

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Releases of the xFitter QCD analysis package

- Versioning convention: **i.j.k** with
  - **i** - stable release
  - **j** - beta release
  - **k** - bug fixes.
- The release notes can be found in this attachment: xFitter_release_notes.pdf .
- Installation script for xFitter together with QCDNUM, APFEL, APPLGRID, LHAPDF install-xfitter
- The script to download coupled data and theory files xfitter-getdata.sh.
- Data and theory files are also stored in hepforge and can be accessed from there ("List of Data Files").

Date	Version	Files	Remarks
03/2017	**2.0.0 FrozenFrog**	xfitter-2.0.0.tgz	stable release with decoupled data and theory files
07/2016	**1.2.2**	xfitter-1.2.2.tgz	release with decoupled data and theory files
05/2016	**1.2.1**	xfitter-1.2.1.tgz	release with decoupled data and theory files
02/2016	**1.2.0**	xfitter-1.2.0.tgz	release with decoupled data and theory files

Sample data files:
LHC: ATLAS, CMS, LHCb
Tevatron: CDF, D0
HERA: H1, ZEUS, Combined
Fixed Target: …
User Supplied: …

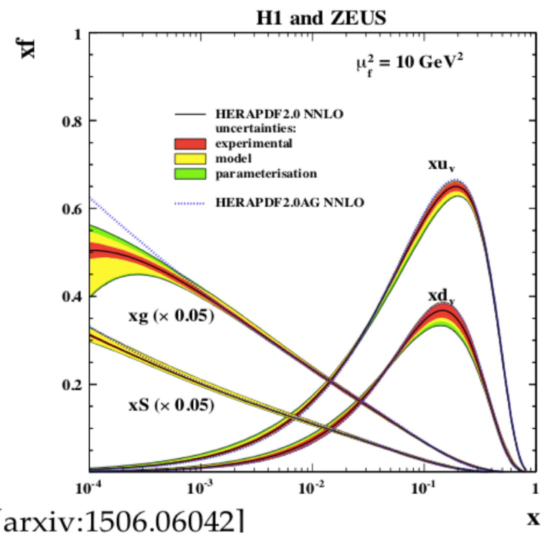
xFitter 2.0.0 FrozenFrog

- Only final combined HERAI+II data are distributed with xFitter
- **getter-xfitter.sh script** to download data with corresponding theory files
- Release 2.0.1 very soon (updates to latest software versions + bug fixes)

https://www.xfitter.org/xFitter/xFitter/DownloadPage

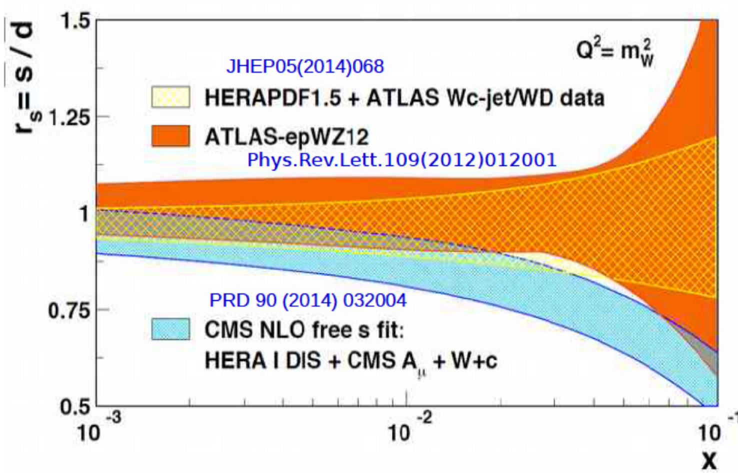
Results obtained with xFitter: Examples

DIS inclusive processes (ep)

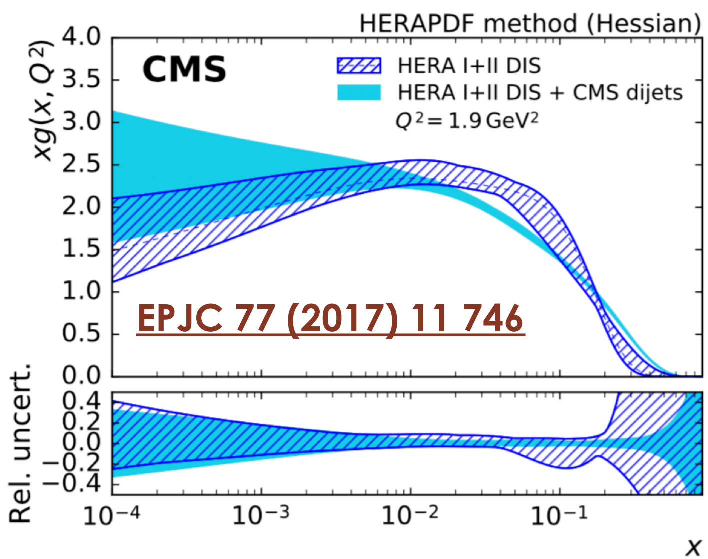


[arxiv:1506.06042]

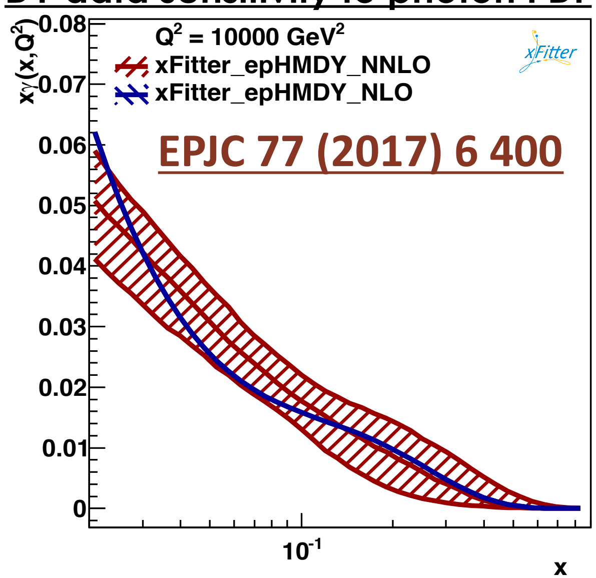
Drell-Yan processes $(pp, p\bar{p})$
(strange quark density determination)



Jet production $(ep, pp, p\bar{p})$



DY data sensitivity to photon PDF



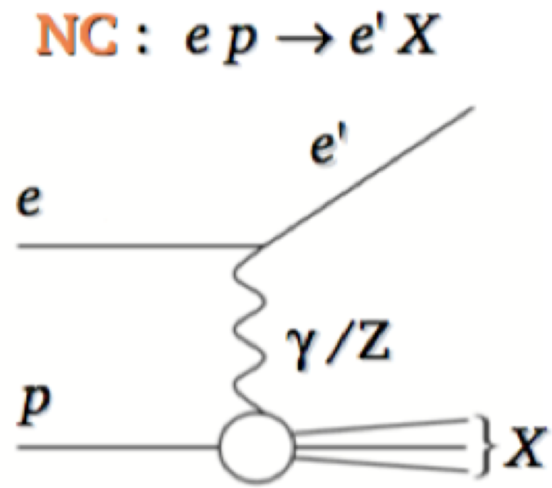
Impact of low-x resummation on QCD analysis of HERA data

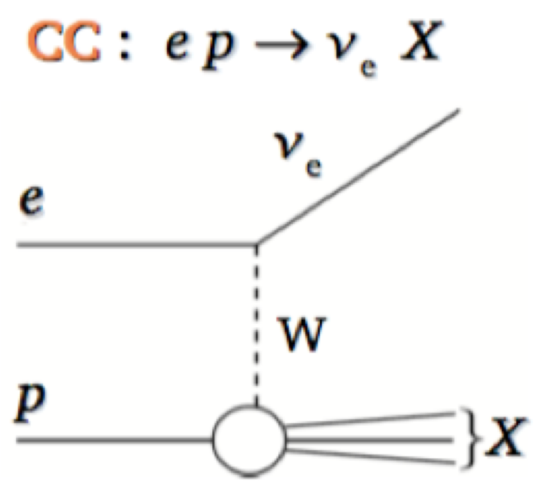
Eur.Phys.J. C78 (2018) no.8, 621
arXiv:1802.00064

xFitter Developers' Team + M. Bonvini

The most precise data to constrain PDFs come from the HERA collider:

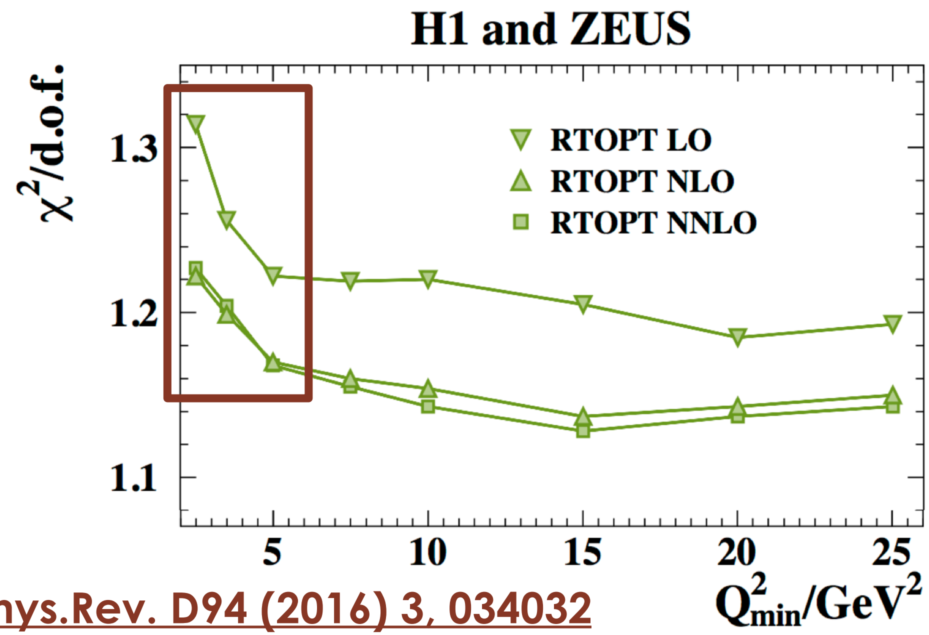
- $e^{\pm}p$ collider at DESY, Hamburg
- $E(e^{\pm})$ = 27.5 GeV
- $E(p)$ = 460-575-820-920 GeV
- H1 and ZEUS experiments at HERA collected ~1fb^{-1} of data
- Types of processes accessible:
  - Neutral Current (NC)
  - Charged Current (CC)



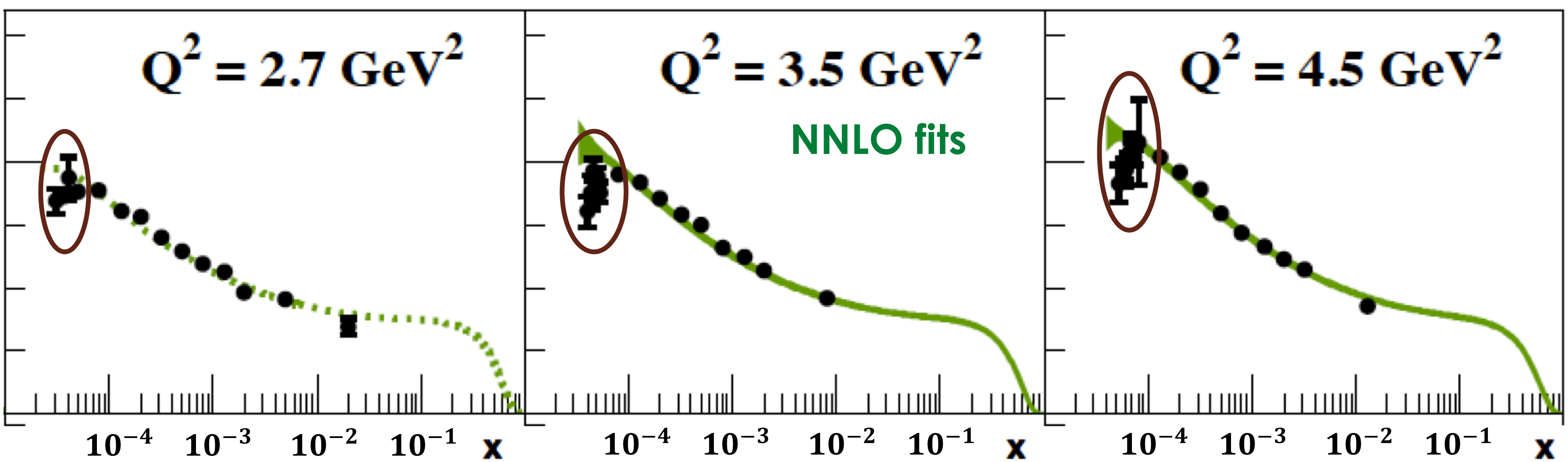


Why are we interested in small-x resummation?

- **Crucial observation**: **low-x** and **low-Q^2** HERA data are not well described by fixed order (FO) perturbative QCD (pQCD)
- Deterioration of χ^2/**ndf** when including data at low-Q^2
- Data turnover at small-x not described by **FO fits**



Phys.Rev. D94 (2016) 3, 034032



Small-x logarithmic enhancement

$$\sigma_{DIS} = C_i \otimes f_i \qquad \mu^2 \frac{\partial}{\partial \mu^2} f_i(\mu) = P_{ij} \otimes f_j(\mu)$$

LO	$\frac{1}{x}\alpha_S^0\,[$	1			$]$
NLO	$\frac{1}{x}\alpha_S\,[$	$\#\log\left(\frac{1}{x}\right)$ +	1		$]$
NNLO	$\frac{1}{x}\alpha_S^2\,[$	$\#\log^2\left(\frac{1}{x}\right)$ +	$\#\log\left(\frac{1}{x}\right)$ +	1	$]$
N³LO	$\frac{1}{x}\alpha_S^3\,[$	$\#\log^3\left(\frac{1}{x}\right)$ +	$\#\log^2\left(\frac{1}{x}\right)$ +	$\#\log\left(\frac{1}{x}\right)$ + 1	$]$
		LL	**NLL**	**NNLL**	

If $\alpha_S \log\left(\frac{1}{x}\right) \sim 1$ → all such terms in the perturbative series are equally important

Reorganisation of the expansion:

$$\frac{1}{x}\left[1 + \#\,\alpha_S \log\left(\frac{1}{x}\right) + \#\,\alpha_S^2 \log^2\left(\frac{1}{x}\right) + \#\,\alpha_S^3 \log^3\left(\frac{1}{x}\right) + \ldots\right] \quad \textbf{(LL)}$$

$$\frac{\alpha_S}{x}\left[1 + \#\,\alpha_S \log\left(\frac{1}{x}\right) + \#\,\alpha_S^2 \log^2\left(\frac{1}{x}\right) + \#\,\alpha_S^3 \log^3\left(\frac{1}{x}\right) + \ldots\right] \quad \textbf{(NLL)}$$

All-order resummation

Small-x resummation

- Small-x resummation formalism based on **k_T-factorization** and **BFKL**
- Resummation affects just the singlet sector (gluon and quark singlet)
- Developed in the 90s-00s

[Catani,Ciafaloni,Colferai,Hautmann,Salam,Stasto]
[Thorne,White][Altarelli,Ball,Forte]

- Recent developments:
  - Improved ABF procedure to resum splitting functions and new formalism for coefficient functions
  - Resummation matched to NNLO, allowing NNLO+NLLx phenomenology
  - Public code: HELL

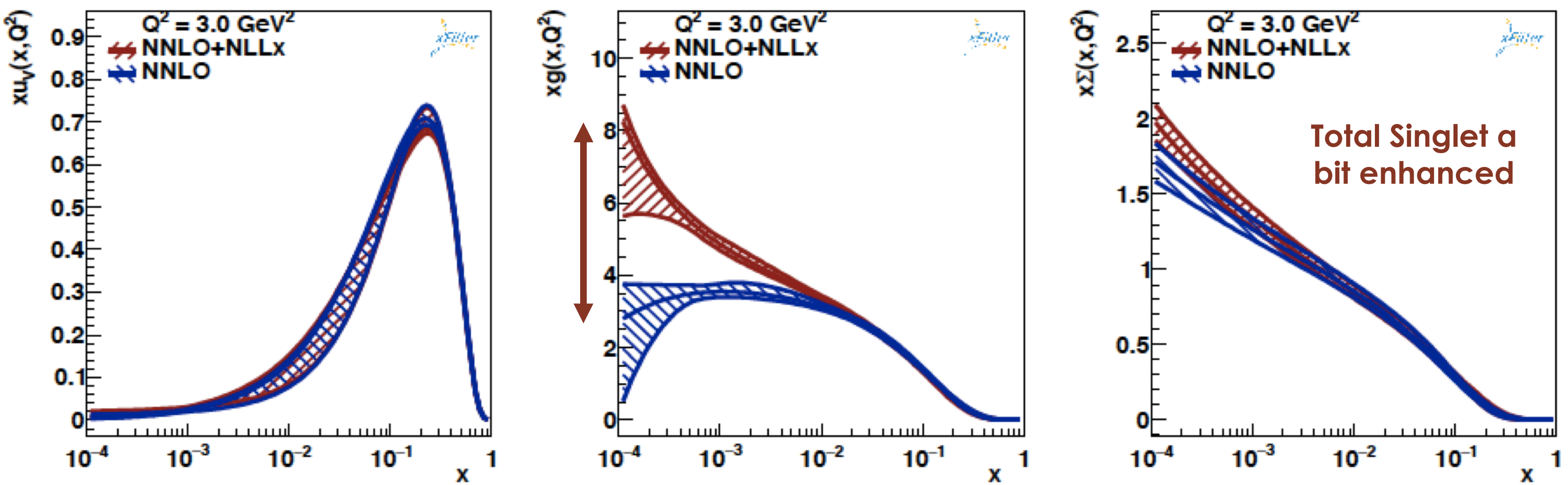
[Bonvini,Marzani,Peraro 1607.02153]
[Bonvini,Marzani,Muselli 1708.07510]

Fit results

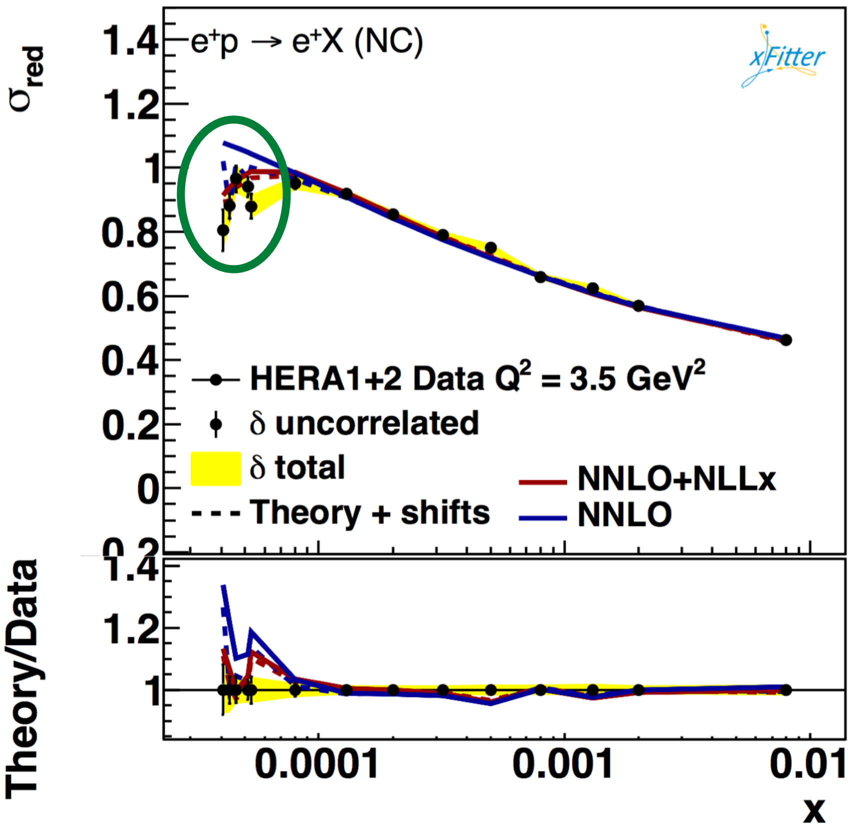
- Fit to combined HERAI+II data
- Significant difference in the gluon PDF
- Other PDFs look about the same

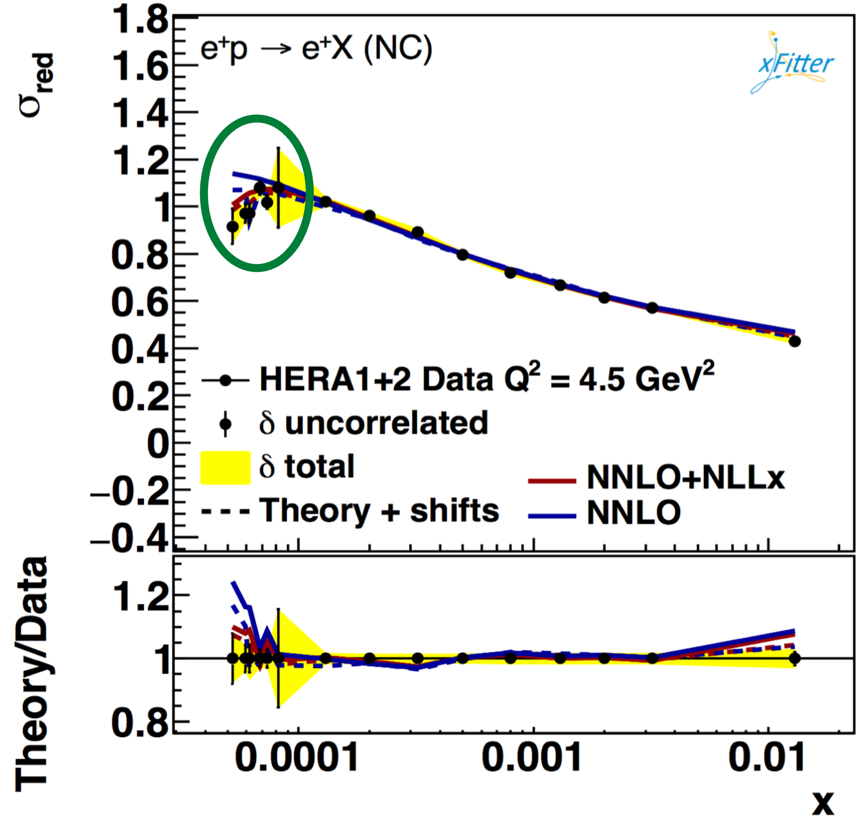
	NNLO	NNLO+NLLx
Total χ^2/d.o.f	1388/1131	1316/1131

Gain in χ^2 of 72 units



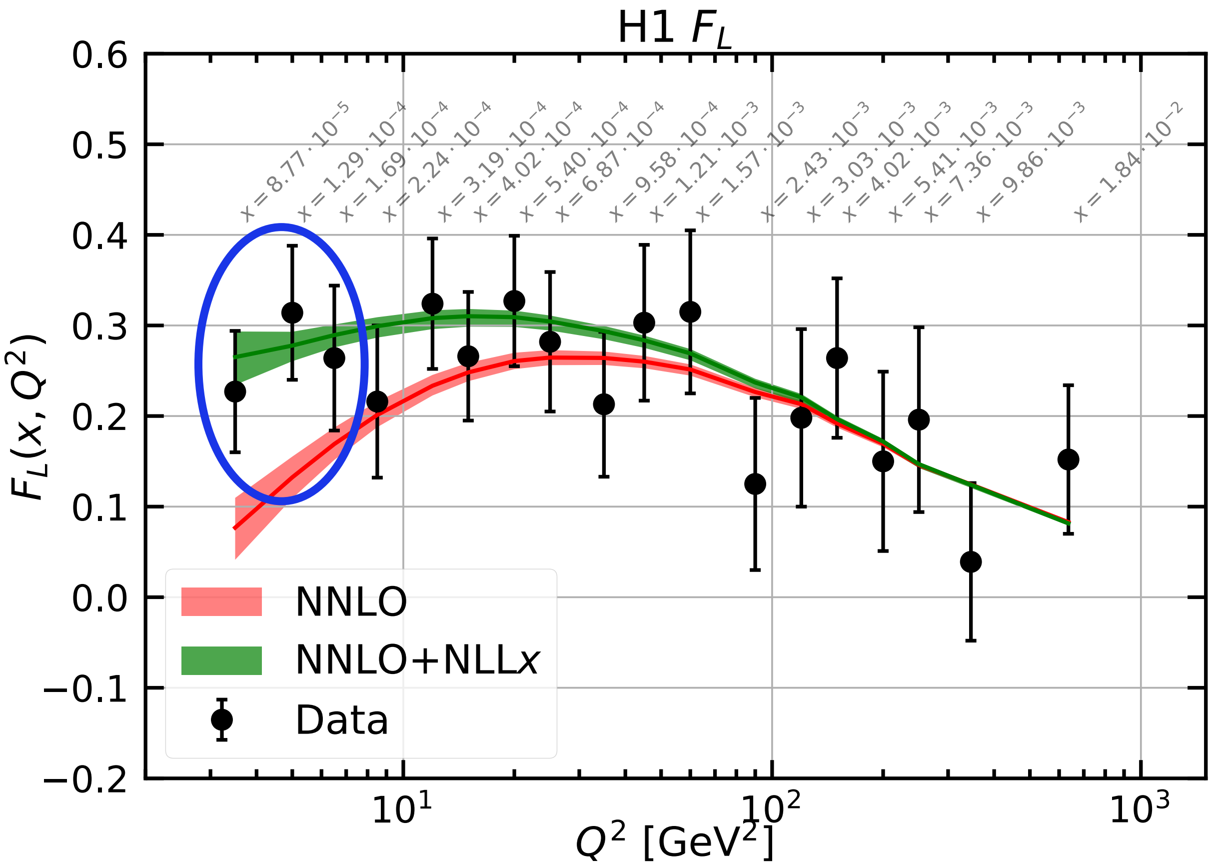
Reduced cross sections





- Better description of the low Q^2 bins
- With the inclusion of resummation, now we are able to describe the turnover of the data

H1 F_L



$$\sigma_{\rm red} = F_2 - \frac{y^2}{Y_+} F_L$$

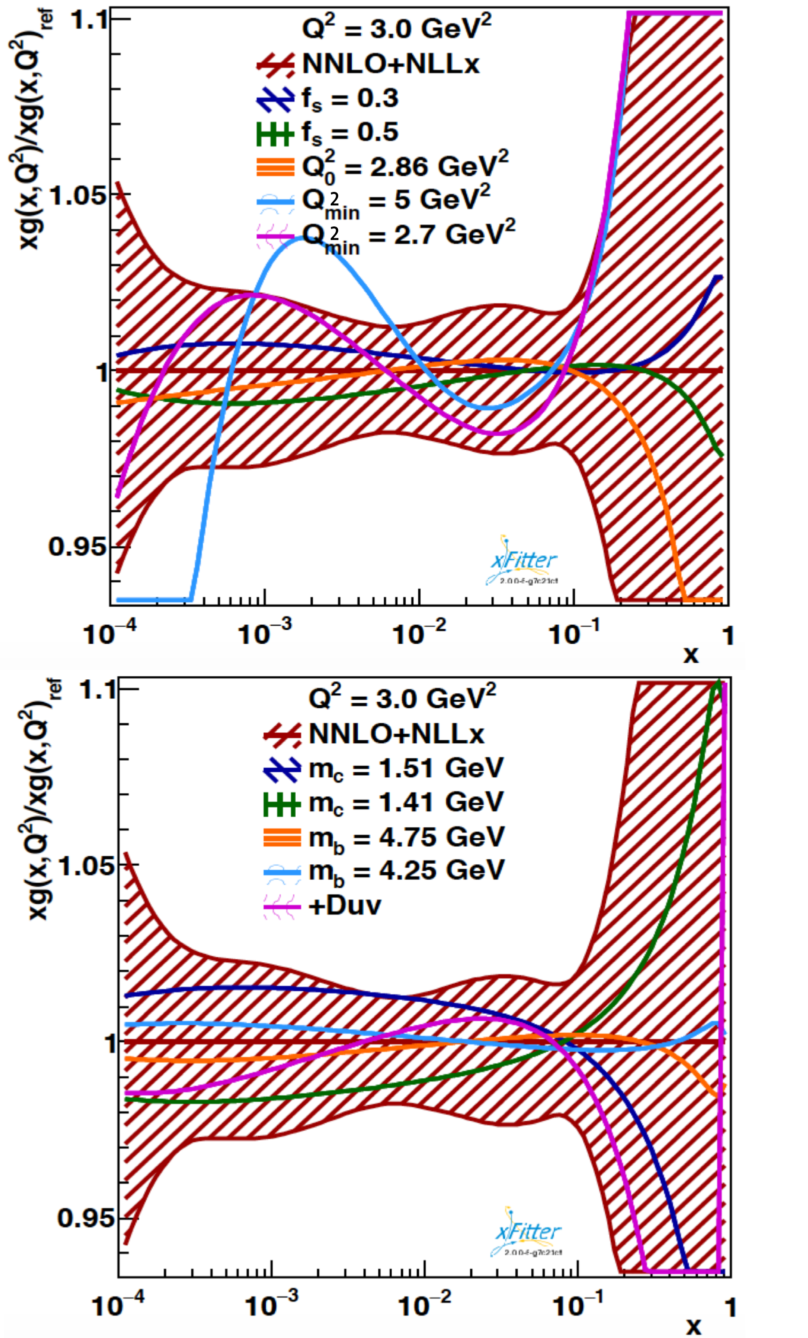
$$Y_+ = (1 + (1 - y)^2)$$
$$y = Q^2/(sx)$$

Better description from the **resummed fit** as compared to the FO one for the H1 F_L extraction (**larger F_L**)

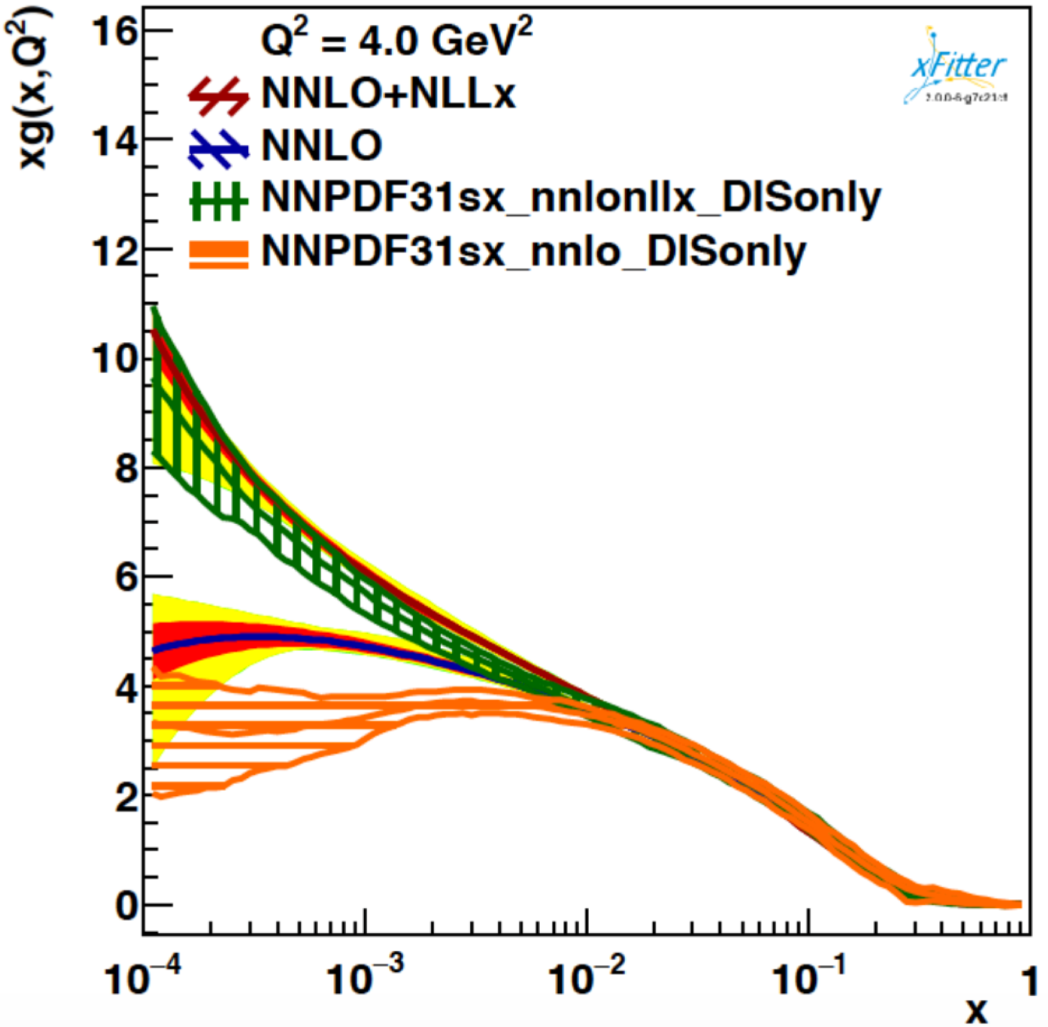
- **F_L proportional to the gluon PDF**
- These data are not (directly) included in our fit → pretty remarkable a-posteriori prediction

Full uncertainty study

- Model variation taken into account:
  - m_c = 1.41 GeV
  - m_c = 1.51 GeV
  - m_b = 4.25 GeV
  - m_b = 4.75 GeV
  - f_s = 0.3
  - f_s = 0.5
  - Q^2_{min} = 2.7 GeV^2
  - Q^2_{min} = 5.0 GeV^2
  - Q^2_0 = 2.86 GeV^2
  - α_s = 0.116
- Parameterisation variation:
  - + Duv (15 parameters in the fit) →
    $xu_v(x) = A_{u_v} x^{B_{u_v}} (1+x)^{C_{u_v}} (1 + \boldsymbol{D_{u_v} x} + E_{u_v} x^2)$
- Q^2_{min} up variation affects the fit more
- **Less tension between data and variations**



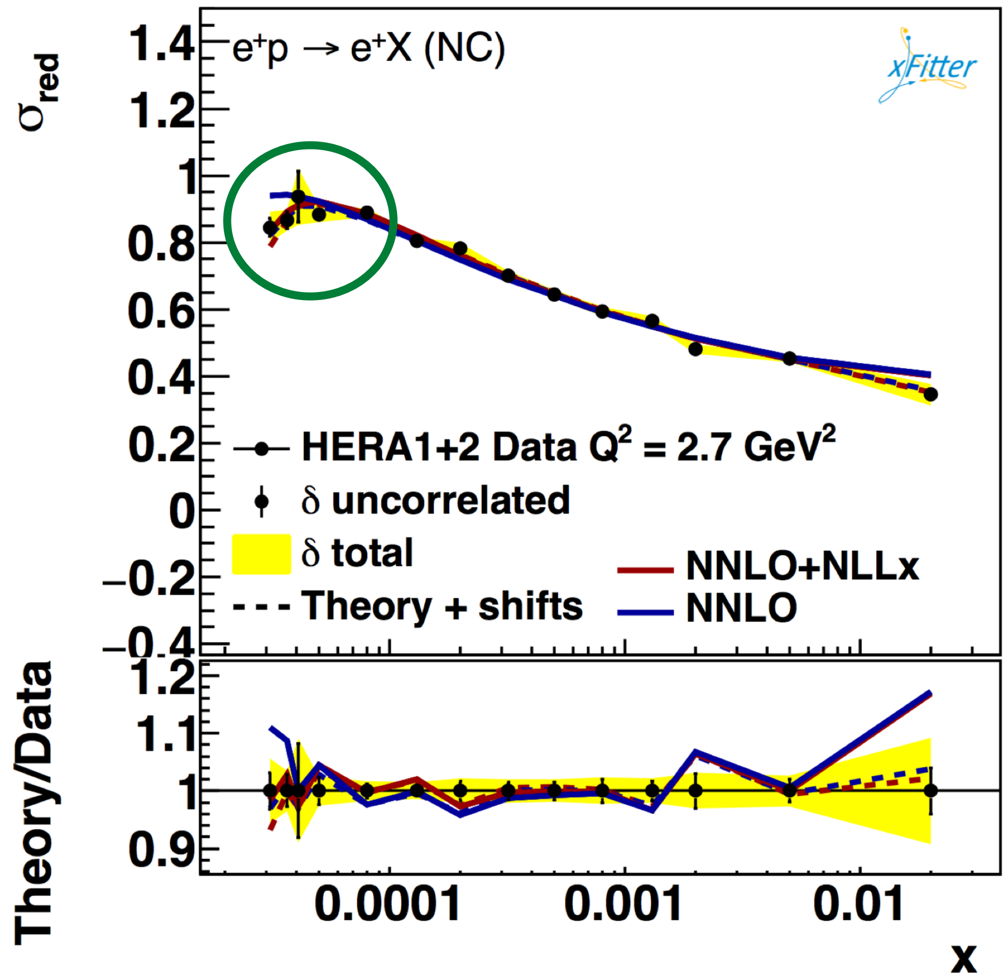
Comparison with NNPDF31 sets



- Fit with small-x resummation corrections by **NNPDF**:
  - Fully-fledged PDF analysis
  - Includes data from other DIS experiments
- **Different treatment of charm PDF:**
  - Our fit → perturbative
  - NNPDF → fitted
- Same qualitative behaviours
- **Nice agreement between the two resummed fits**

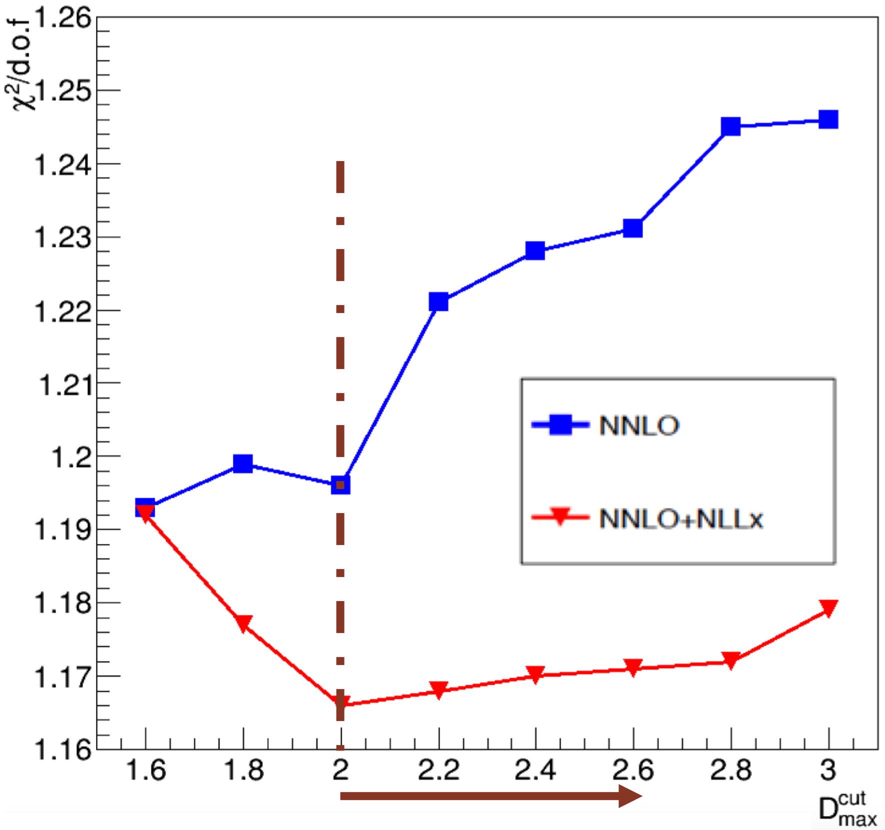
The Q^2 = 2.7 GeV^2 bin

- We tried to include Q^2 = 2.7 GeV^2 bin in the fit as well
- The fit with log(1/x) resummation describes these data points better than the FO fit
- The PDFs derived from the fits including this extra Q^2 bin are basically identical to those already shown
- **Another triumph for small-x resummation**

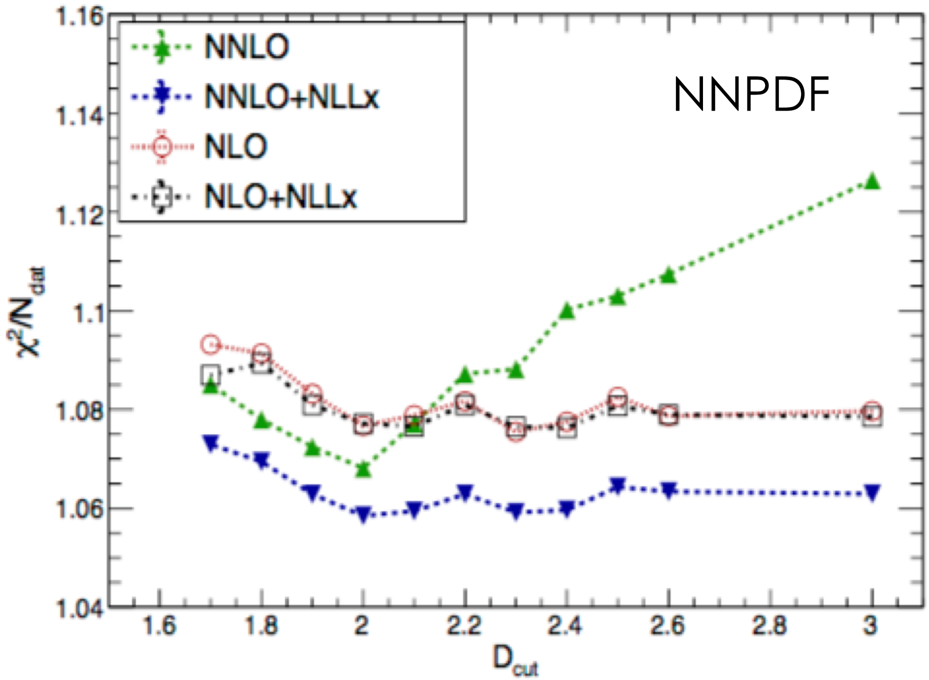


Where is the resummation important?

Simultaneous cut on Q² and x implemented: $\alpha_s(Q^2)\log\left(\frac{1}{x}\right) \geq D_{cut}$



EPJC 78 (2018) 4 321



Consistent with what has been found in the NNPDF paper

Is this the best possible fit to HERA data? Are our PDFs reliable?

- Resulting fitted PDFs depend on various aspects:
  - Perturbative order of partonic cross sections/DGLAP splitting functions
  - The way heavy quarks are treated
  - The choice of unphysical scales e.g. μ_R or μ_F
  - Fitting methodology (χ^2 definition, minimization methods, …)
  - <u>The choice of the parametrization</u>
  - Theoretical inputs
  - …
- A good parametrization is one that is able to describe the data with the least possible bias
- At the same time, it has to keep a sufficiently small number of parameters in order to avoid overfitting
- The question to answer is: **do we trust the PDF parametrization used so far?**

Default HERAPDF (xFitter) parametrisation

$$xg(x,\mu_0^2) = A_g\, x^{B_g}(1-x)^{C_g} - A'_g\, x^{B'_g}(1-x)^{C'_g}$$

$$xu_v(x,\mu_0^2) = A_{u_v}\, x^{B_{u_v}}(1-x)^{C_{u_v}}\left[1+E_{u_v}x^2\right]$$

$$xd_v(x,\mu_0^2) = A_{d_v}\, x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{u}(x,\mu_0^2) = A_{\bar{u}}\, x^{B_{\bar{u}}}(1-x)^{C_{\bar{u}}}\left[1+D_{\bar{u}}x\right]$$

$$x\bar{d}(x,\mu_0^2) = A_{\bar{d}}\, x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}}$$

- **Is this parameterisation flexible enough?** Limited structure at small-x → shape strongly dominated by asymptotic behaviour of x^B
- **More flexibility in the small-x regime is needed**
- It is also very important in the light of future higher-energy colliders:
  - Large Hadron-electron Collider (LHeC)
  - Future Circular electron-hadron or hadron-hadron Colliders (FCC)

Newly proposed parametrization

- Asymptotic behaviours:

$$x^B(1-x)^C$$

- To model large-x region → Polynomial in x

$$(1+Dx+Ex^2+\cdots)$$

- To model small-x region → Polynomial in $\log(x)$

$$(1+F\log(x)+G\log^2(x)+H\log^3(x)+\cdots)$$

- We considered both a multiplicative and an additive option, and we chose the latter:

$$xf(x,\mu_0^2)=A\,x^B(1-x)^C\left[1+Dx+Ex^2+F\log x+G\log^2 x+H\log^3 x\right]$$

arXiv:1902.11125 [Bonvini,FG]

The actual parametrization

$$xg(x,\mu_0^2) = A_g\, x^{B_g}(1-x)^{C_g}\left[1 + F_g \log x + G_g \log^2 x\right]$$

$$xu_v(x,\mu_0^2) = A_{u_v}\, x^{B_{u_v}}(1-x)^{C_{u_v}}\left[1 + E_{u_v}x^2 + F_{u_v} \log x + G_{u_v} \log^2 x\right]$$

$$xd_v(x,\mu_0^2) = A_{d_v}\, x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{u}(x,\mu_0^2) = A_{\bar{u}}\, x^{B_{\bar{u}}}(1-x)^{C_{\bar{u}}}\left[1 + D_{\bar{u}}x + F_{\bar{u}} \log x\right]$$

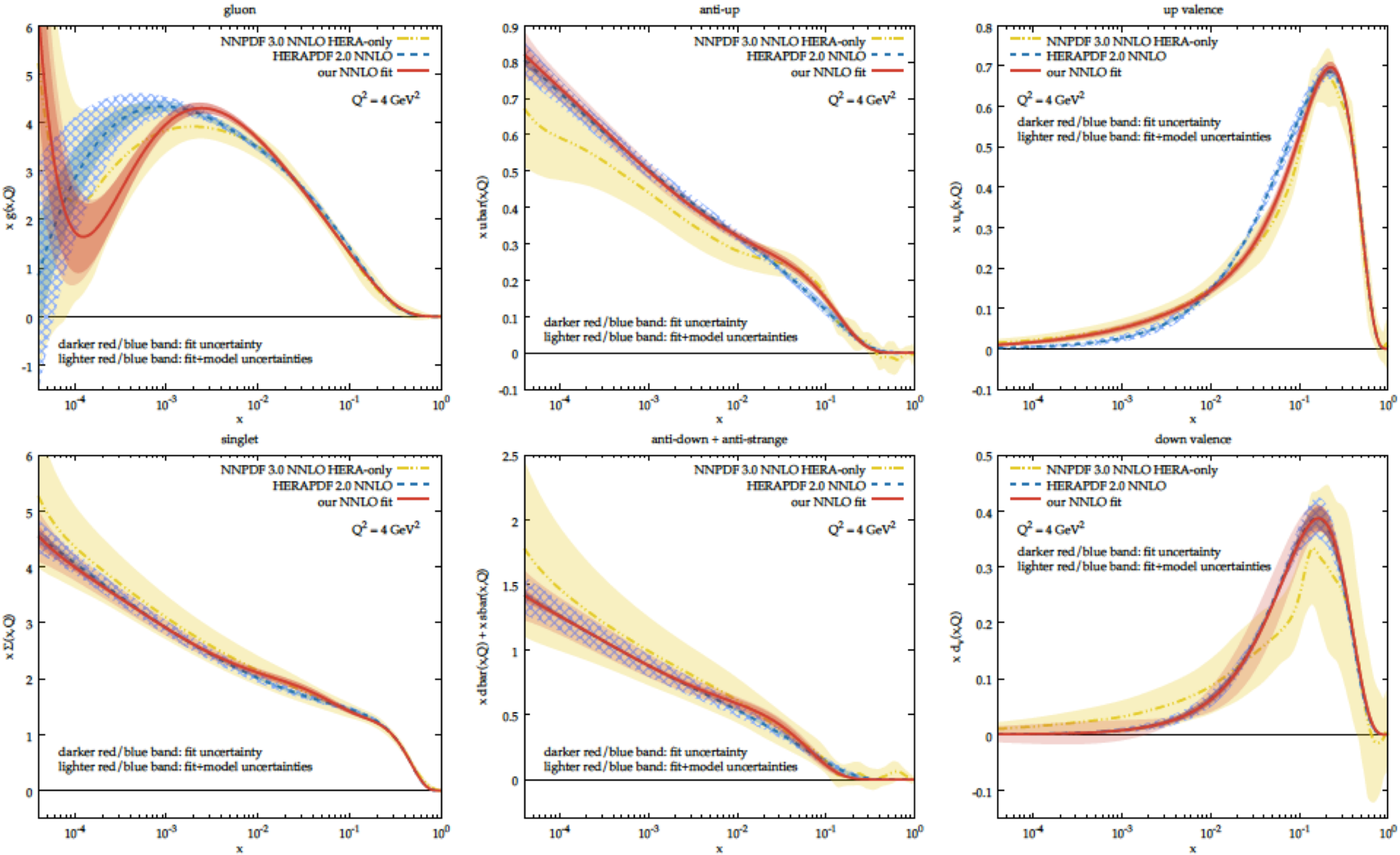
$$x\bar{d}(x,\mu_0^2) = A_{\bar{d}}\, x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}}\left[1 + D_{\bar{d}}x + F_{\bar{d}} \log x\right],$$

- Our new PDF parametrization:
  - Depends on 18 free parameters that must be fitted (to be compared with HERAPDF2.0 that has 14 free parameters)
  - Two extra parameters for u_V
  - Two extra parameters for $\bar{u}$ and $\bar{d}$
  - Major improvement comes from the gluon PDF (same number of free parameters)

Fit results

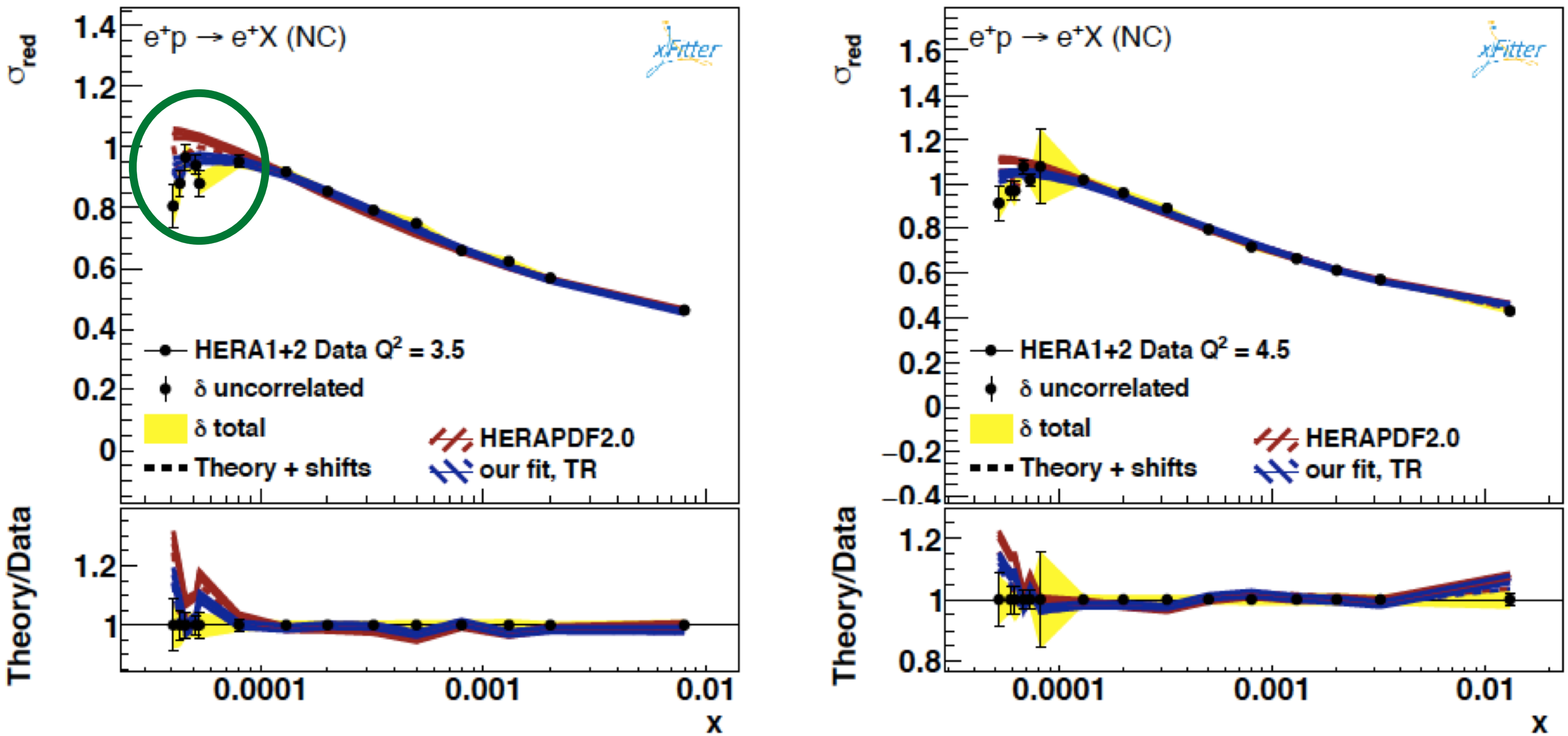
Contribution to χ^2	Old parametrization	New parametrization
subset NC e^+ 920 $\tilde{\chi}^2$/n.d.p.	451/377	406/377
subset NC e^+ 820 $\tilde{\chi}^2$/n.d.p.	68/70	74/70
subset NC e^+ 575 $\tilde{\chi}^2$/n.d.p.	220/254	222/254
subset NC e^+ 460 $\tilde{\chi}^2$/n.d.p.	218/204	225/204
subset NC e^- $\tilde{\chi}^2$/n.d.p.	215/159	217/159
subset CC e^+ $\tilde{\chi}^2$/n.d.p.	44/39	37/39
subset CC e^- $\tilde{\chi}^2$/n.d.p.	57/42	50/42
correlation term + log term	100 + 15	79 + 2
Total χ^2/d.o.f.	**1388/1131**	**1312/1127**

- Significant reduction in the total χ^2
- **Significant difference also at PDF level**



- We combined all the uncertainties (**exp+th+model**)
- Our final PDF set is largely compatible with the (more unbiased) NNPDF set

How could the fit quality improve so much?



- In most of the cases the agreement is at the same level
- Exception for low-Q^2 and low-x data, where **now we can reproduce the turnover** of the data (in a FO fit!)
- This region is where the impact of log(1/x) terms is expected to be largest
- χ^2 improvement of the same size as the one found previously due to the inclusion of small-x resummation – **is resummation really needed?**

Including small-x resummation

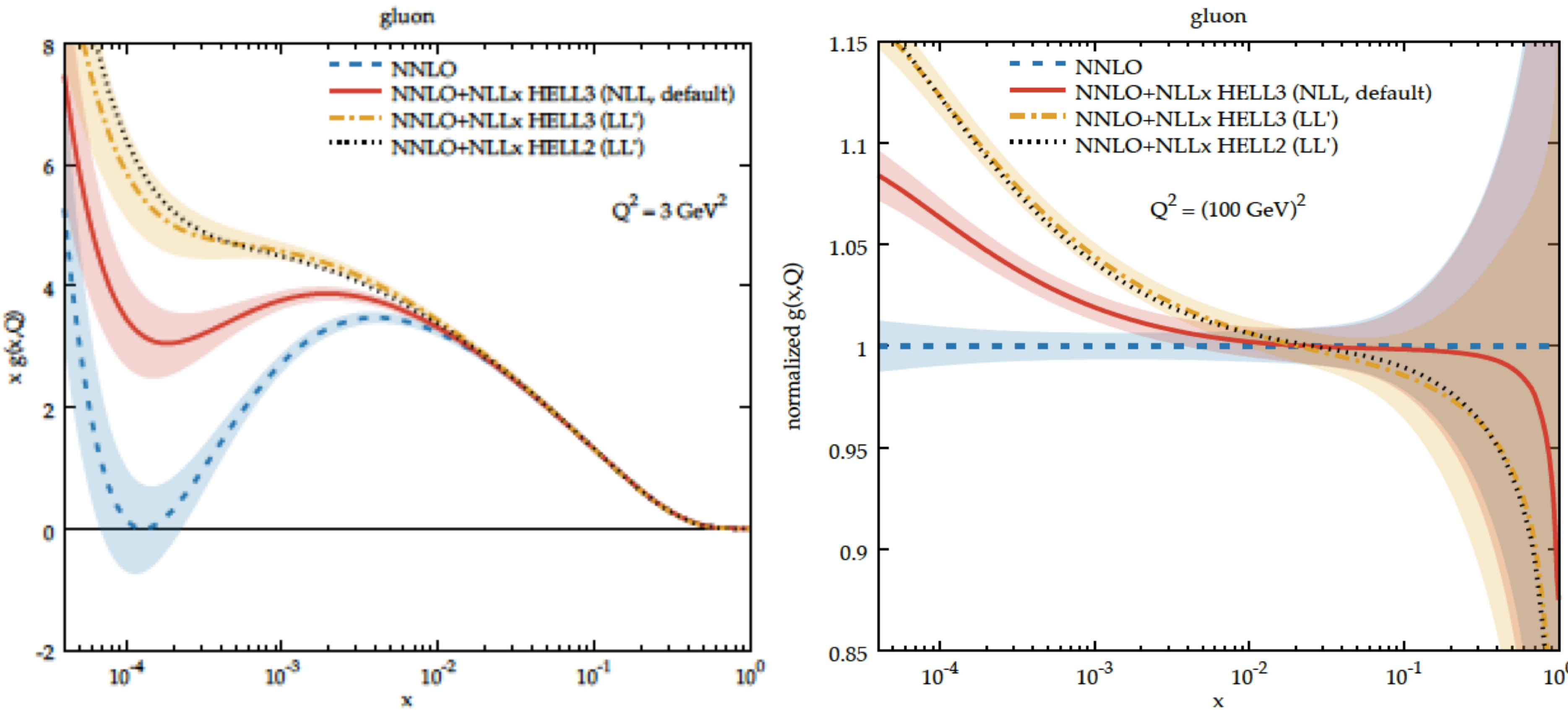
- Done using HELL 3.0 for **the first time** – 1805.08785, 1805.06460, 1708.07510
- It provides resummed contributions to the DGLAP splitting functions, the heavy quark matching conditions and the DIS coefficient functions at NLLx

Contribution to χ^2	HELL3.0 (NLL)	HELL3.0 (LL′)	HELL2.0 (LL′)
subset NC e^+ 920 $\tilde{\chi}^2$/n.d.p.	402/377	403/377	403/377
subset NC e^+ 820 $\tilde{\chi}^2$/n.d.p.	70/70	69/70	69/70
subset NC e^+ 575 $\tilde{\chi}^2$/n.d.p.	219/254	219/254	218/254
subset NC e^+ 460 $\tilde{\chi}^2$/n.d.p.	223/204	224/204	224/204
subset NC e^- $\tilde{\chi}^2$/n.d.p.	219/159	220/159	220/159
subset CC e^+ $\tilde{\chi}^2$/n.d.p.	38/39	38/39	38/39
subset CC e^- $\tilde{\chi}^2$/n.d.p.	49/42	49/42	49/42
correlation term + log term	73 − 7	72 − 11	72 − 10
Total χ^2/d.o.f.	**1284/1127**	**1283/1127**	**1283/1127**

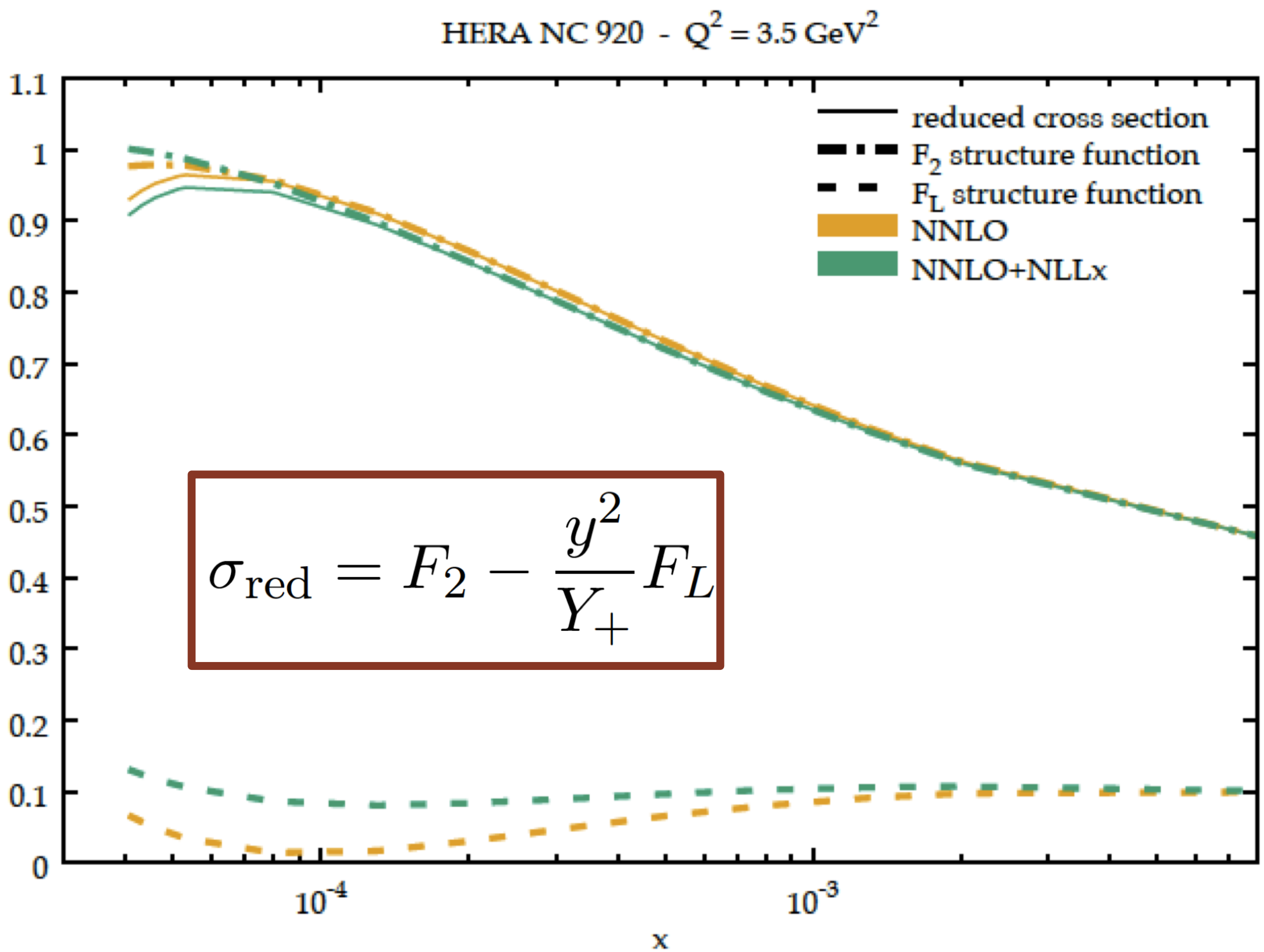
- If compared to NNLO fit, further reduction of ~30 units in χ^2

Including small-x resummation

- The difference between two versions of HELL v3.0 is the introduction of a new default treatment of subleading logarithmic contributions
- These contributions may change the size of the effect resummation on the PDFs, but they remain rather different from their respective NNLO version



Reduced cross section, F_2 and F_L



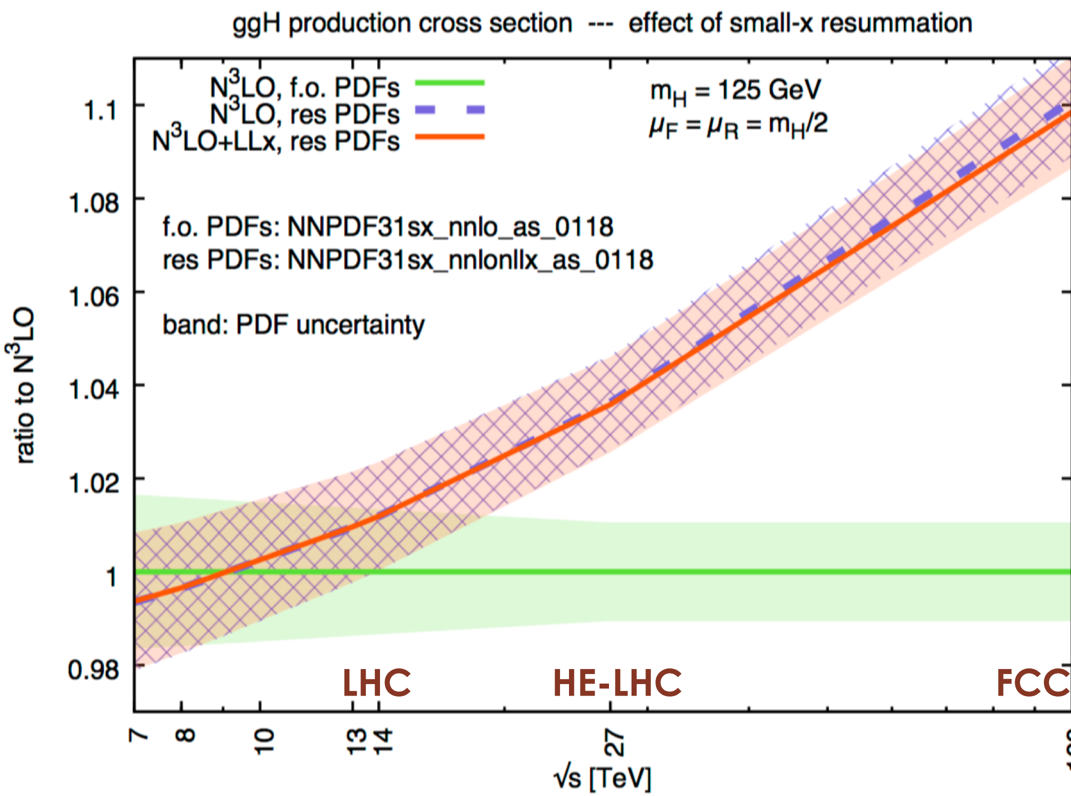
$$\sigma_{\rm red} = F_2 - \frac{y^2}{Y_+} F_L$$

Where $Y_+ = (1 + (1 - y)^2)$ and $y = Q^2/(sx)$

- FO and resumed calculations very similar for the reduced xsec
- NNLO prediction for F_2 decreases at small x (softer gluon and quark singlet), while it rises steadily at resumed level (larger singlet)
- Resummed F_L is quite flat in x and much larger than the NNLO one ($x \lesssim 10^{-3}$)
- Rise of F_L due to the gluon PDF shape (rising for $x \sim 10^{-4}$)

Resummed phenomenology

- Inclusive **gluon-fusion Higgs** production process



- Resummed calculation matched to N^{3}LO FO calculations
- Small-x resummation has a modest impact at current LHC energies
- Its impact grows substantially with the energy, reaching 10% at 100 TeV
- **Bulk of the effect:** the resummed PDFs and their resummed evolution

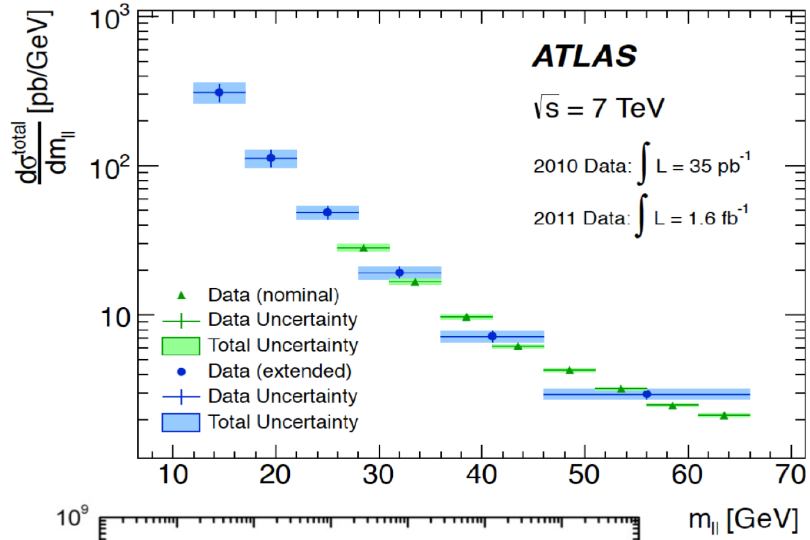
Phys.Rev.Lett. 120 (2018) 20 202003 **[Bonvini,Marzani]**

Eur.Phys.J. C78 (2018) no.10, 834 **[Bonvini]**

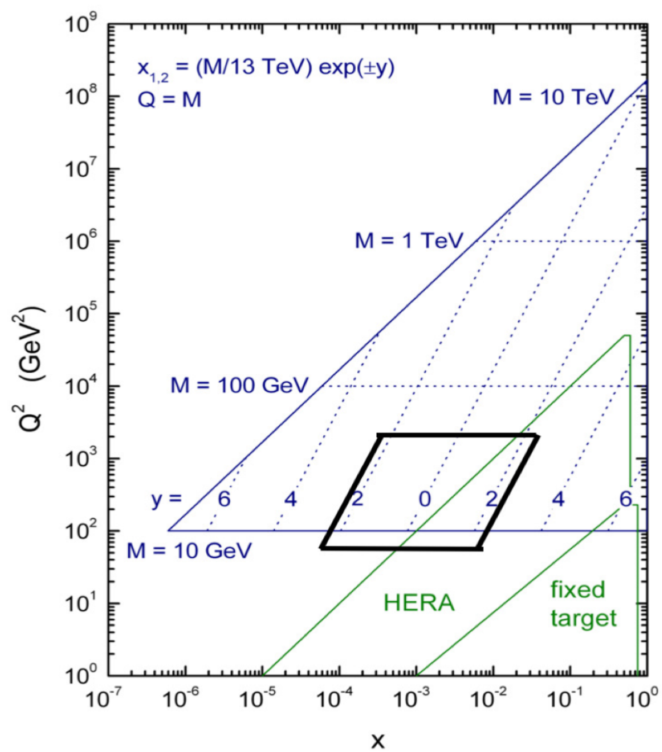
- Here inclusive cross sections BUT a more prominent effect is expected in exclusive/differential cross section (especially in e.g. large-rapidity regions)

Low-mass DY @13 TeV

JHEP 06 (2014) 112

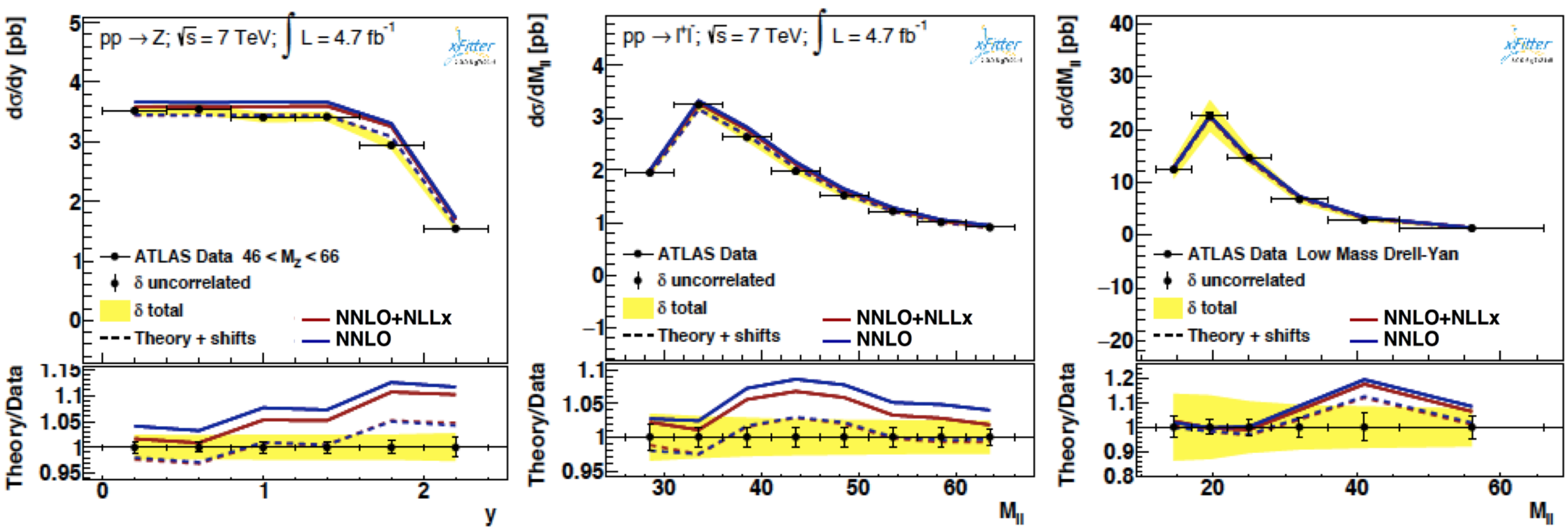


- e/μ decay channels for invariant masses between 26 GeV and 66 GeV using 1.6 fb^{-1} of data collected in 2011
- Then analysis extended as low as 12 GeV in the muon channel using 35 pb^{-1} of data collected in 2010
- In order to provide information that advances our knowledge of the PDFs – **low-x region**
- For the Run II analysis, **the results will be muon channel-only**
- Just 2015 dataset in use (3.2 fb^{-1})
- Cross sections provided both as $d\sigma/dm_{\mu\mu}$ (1D) and $d^2\sigma/dm_{\mu\mu}d|y_{\mu\mu}|$ (2D)
- **First ATLAS analysis** including the **7-9 GeV bin** for cross section measurements



First look at low-mass DY ATLAS data and low-mass Z sideband @7 TeV

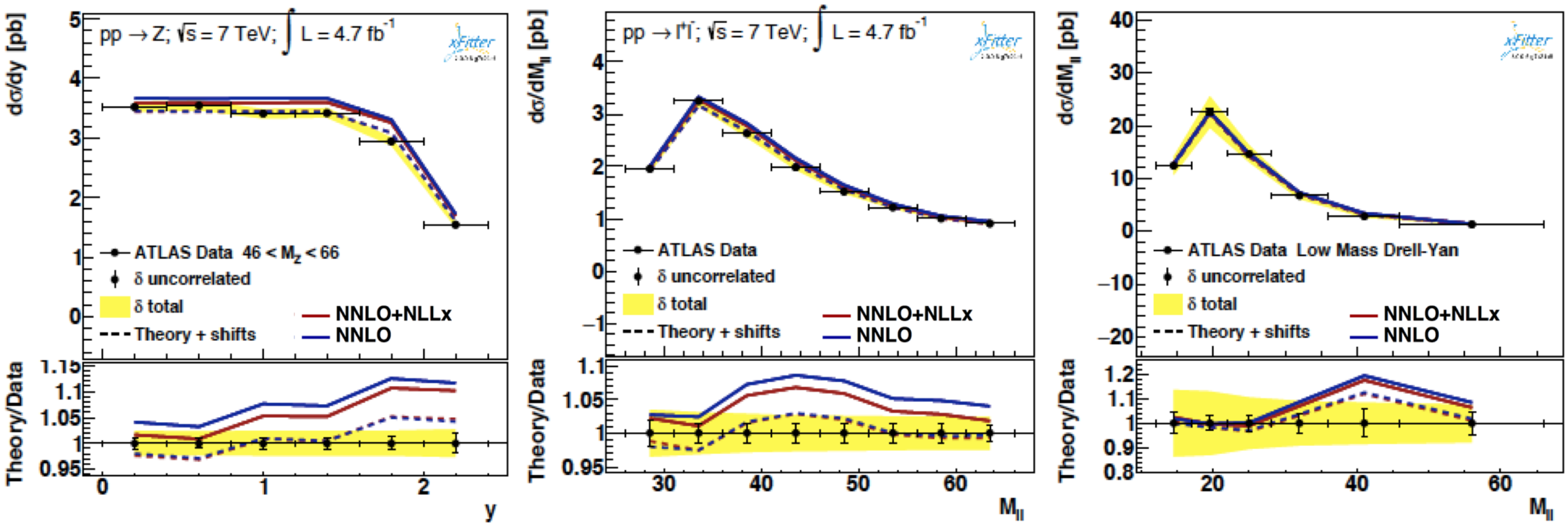
- First look at the description of the following data samples:
  - low-mass DY
  - W,Z precision measurement - **EPJC 77 (2017) 6 367**



- Description slightly improved when using the small-x resummation for the low mass DY data
- As regards the low mass Z sideband, NLLx resummation doesn't help

First look at low-mass DY ATLAS data and low-mass Z sideband @7 TeV

- First look at the description of the following data samples:
  - low-mass DY
  - W,Z precision measurement - **EPJC 77 (2017) 6 367**



- We cannot perform resummed fit including these data (**resummed hard process cross section not available yet**) – resummation available just in the PDF evolution

Work in progress (Bonvini, Marzani et al.)

Summary

- Study on the impact of small-x resummation on the HERA data arXiv:1802.00064
- **Gain of 74 units in χ^2 wrt the FO NNLO fit**
- Significant difference in $xg(x, Q^2)$; **gluon no longer decreases at small x**
- **New simple parametrization** for the PDFs at the initial scale that includes a low degree polynominal in log(x) arXiv:1902.11125
- Improvement of the fit quality (62 units reduction in χ^2 wrt HERAPDF2.0 at NNLO)
- Accomplished using **18 parameters** (only 4 more than HERAPDF2.0)
- Further including the resummation of small-x logarithms → gain of ~30 units in χ^2
- Implications of small-x resummation for physics at LHC
  - Inclusive gF Higgs production cross section
  - Drell-Yan
- Low-mass DY at 13 TeV: new ATLAS measurement coming out soon
- **Small-x resummation crucial for low-x (HERA/LHC/FCC) phenomenology**

Backup Slides

xFitter on Hepforge: data access

http://xfitter.hepforge.org/

- This website contains complementary information to https://www.xfitter.org/
- Possibility to download data files (including theory)
- Updated automatically with new data added to svn

Your feedback is welcome! ☺
(via email xfitter-help@desy.de)

http://xfitter.hepforge.org/data.html

This page contains the list of publicly available experimental data sets (with corresponding theory grids if available) in the xFitter package.
To download data set please click on the arXiv link (and open/save tar.gz file).

No	Collider	Experiment	Reaction	arXiv	Readme
1	fixedTarget	bcdms	inclusiveDis	cern-ep-89-06	README
2	hera	h1	beautyProduction	0907.2643	
3	hera	h1	inclusiveDis	1012.4355	
4	hera	h1	jets	0706.3722	README
5	hera	h1	jets	0707.4057	README
6	hera	h1	jets	0904.3870	README
7	hera	h1	jets	0911.5678	README
8	hera	h1	jets	1406.4709	README
9	hera	h1zeusCombined	charmProduction	1211.1182	
10	hera	h1zeusCombined	inclusiveDis	0911.0884	
11	hera	h1zeusCombined	inclusiveDis	1506.06042	
12	hera	zeus	beautyProduction	1405.6915	
13	hera	zeus	diffractiveDis	0812.2003	
14	hera	zeus	jets	0208037	
15	hera	zeus	jets	0608048	
16	hera	zeus	jets	1010.6167	
17	lhc	atlas	drellYan	1305.4192	
18	lhc	atlas	drellYan	1404.1212	
19	lhc	atlas	jets	1112.6297	

(more datasets available on the website)

Novelties in xFitter 2.0.0 (1)

Release	Date	Description
`xfitter-2.0.0` (FrozenFrog)	20.03.2017	**Physics related additions:** • Implementation of switching scales for heavy quarks (APFEL) • Fast convolution using APFELGRID ("fk" tables) • Write out top LHAPDF if top mass is below kinematic limit (5 and 6 flavour PDFs) • Extra PDF parameters of the photon parametrisation • Improvements to QED evolution interface (QEDevol) • (optionally) Produce symmetric hessian PDF sets using minuit HESSE covariance matrix computation instead of default ITERATE method. • Updates to dipole steering files, saturation flag added • Extra option to separate statistical uncertainty from total covariance matrix, when it is uncorrelated **Technical improvements:** • Move to QCDNUM 17-01-13 new PDF interfaces. Make use of fast PDF calls. • Update fastNLO to latest version. Switch from APPLGRID → FastNLO to native FastNLO. • `install-xfitter` script uses cvmfs (recommended way to install xFitter) • `xfitter-getdata.sh` script added to download datasets • Added new datasets from LHC and HERA, and LHeC simulated data. • Synchronisation of the lhapdf6 output grid with initialisation from QCDNUM • Restore optional LHAPDFv5 usage

!!

Novelties in xFitter 2.0.0 (2)

Release	Date	Description
xfitter-2.0.0 (FrozenFrog)	20.03.2017	**Physics related additions:**

- Possibility to force PDFs to be positive after processing (`xfitter-process` tool)
- Adjustment of internal systematic arrays to to run with all data. Reduction of other internal arrays to keep memory footprint low
- Improvements in configuration and makefiles to work with different compilers and operation systems
- If `OUTPUTDIR` directory exists when running xfitter, it will be moved to `OUTPUTDIR_OLD`
- Increased the possible length of the output directory name
- Clean up (removing/renaming functions, suppressing unneeded outputs)
- Updates to README, INSTALLATION, steering files, manual, doxygen config
- Add error message if combine utility is used with LHAPDFv 5.x
- Cleanup of warning messages, better indication of potential problems
- Restore `make dist` functionality
- Added extra automatic checks
- Add feature to draw individual sets by using set:ID:dir syntax
- Additional option `--loose-mc-replica-selection`
- Add strict check for second option of MC-replica path matching
- Other small fixes in drawing options (logo, coloured error bands, etc)

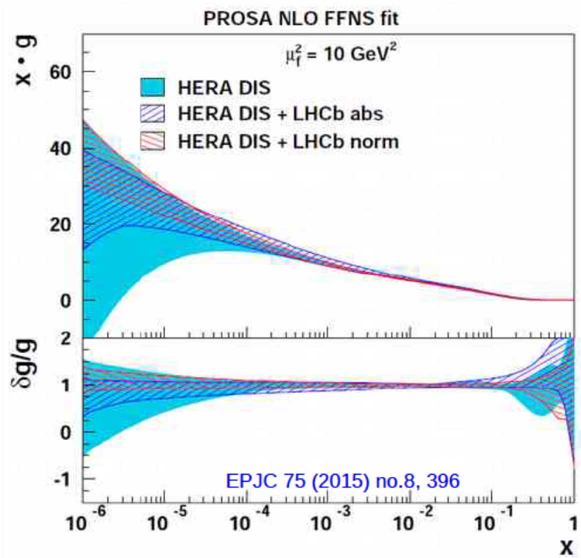
Bug Fixes:

- Fix in the gluon parametrisation (affecting HERAPDF parameterisation sum-rule)
- Enable compilation with LHAPDF6 and without APPLgrid
- Fixes in non-standard parameterisations (e.g. using Chebyshev polynomials)
- Fix few conflicting fortran symbols.

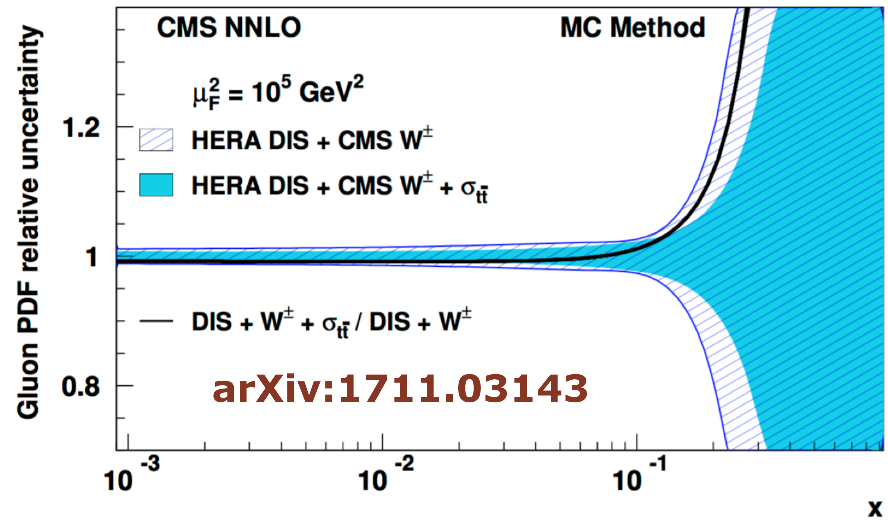
flavour PDFs)
SE covariance
matrix, when
PDF calls.
NLO to native
Fitter)
ta.
QCDNUM

Results obtained with xFitter: Examples (2)

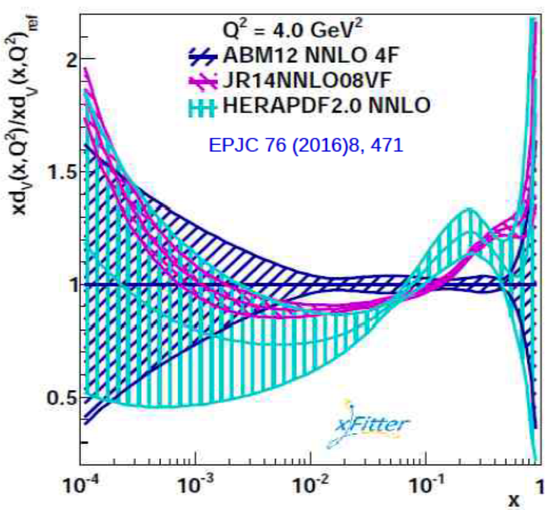
Heavy quark production($ep, pp, p\bar{p}$)



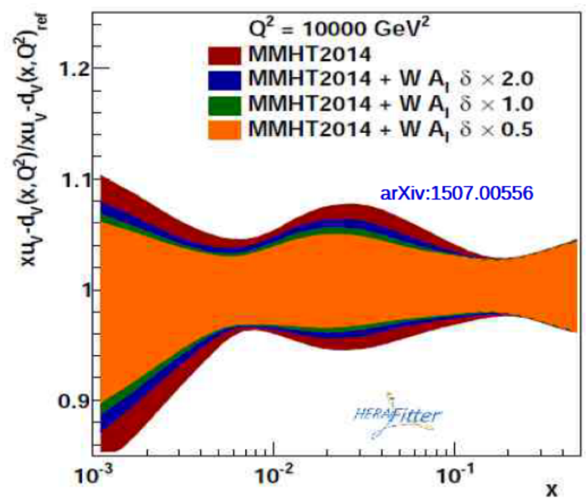
Top-quark production ($pp, p\bar{p}$)



Evolution of moder PDFs (benchmarking)



PDF4LHC report (benchmarking)

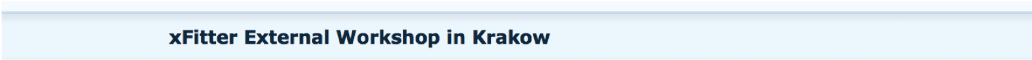


Last xFitter Developers Meeting

External xFitter's meeting in Krakow:

- 31 participants
- 3 days workshop with number of talks and many discussions

https://indico.desy.de/indico/event/19213/overview


xFitter External Workshop in Krakow

The third international workshop to bring together users and developers of the xFitter project. The topics will include current status and further developments in accordance with experimental analysis demands.

The programme of the workshop will be from Monday 5th morning till Wednesday 7th lunch time. Participants should arrive Sunday 4th. Welcome reception will be held in the Krakow University of Technology, St. Warszawska 24, Bldg.10-24, room 108, Gallery Gil from 7pm on Sunday. The workshop will end with lunch on Wednesday March 7th. Some limited financial help for attendance at the workshop is available from DESY and Krakow University of Technology.

xFitter workshops

xFitter examples (CTEQ school)

http://qcd2016.desy.de/

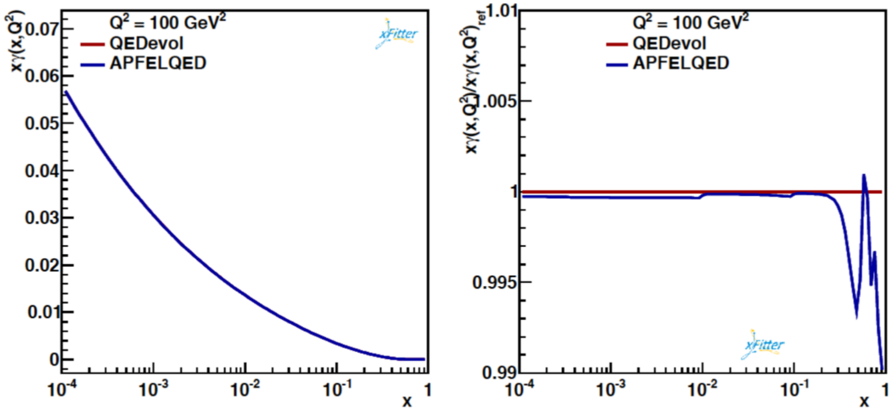
Stefano Camarda
Ringailé Plačakyté

A list of educational examples are provided in the package - prepared for the CTEQ summer school 2016:

- **Exercise 1:** PDF fit
  - learn the basic settings of a QCD analysis, based on HERA data only
- **Exercise 2:** Simultaneous PDF fit and as
  - learn the basic of an as extraction using H1 jet data
- **Exercise 3:** LHAPDF analysis
  - how to estimate impact of a new data without fitting:
  - profiling and reweighting techniques
- **Exercise 4:** Plotting LHAPDF files
  - direct visualisation of PDFs from LHAPDF6 using simple python scripts
- **Exercise 5:** Equivalence of χ^2 representations
  - understand different χ^2 representations (nuisance parameters and covariance matrix χ^2 formulas)

Physics cases in xFitter

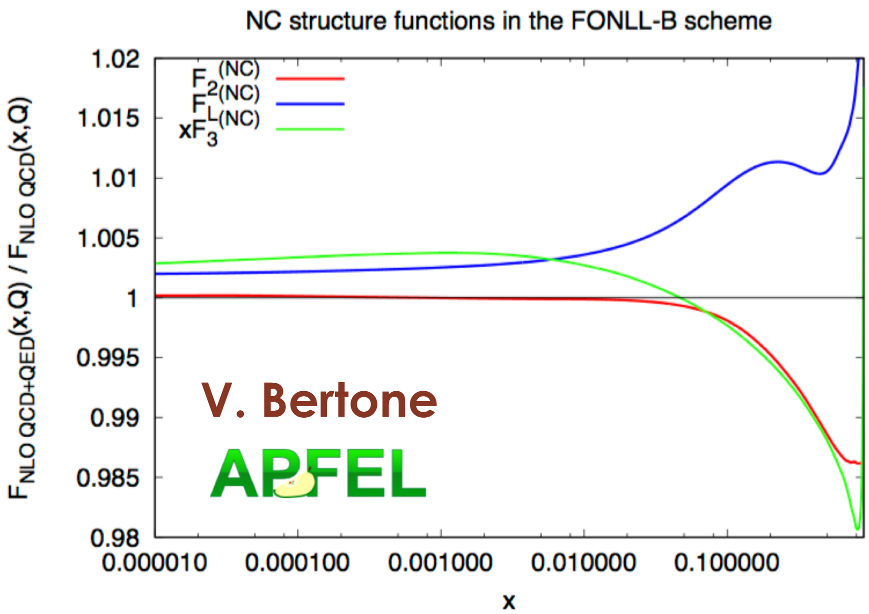
- **New QED PDFs up to NNLO QCD + NLO QED** in FFNS and VFNS are now available via evolutions in:
  - QCDNUM adjusted for DGLAP+QED [R. Sadykov] http://www.nikhef.nl/~h24/qcdnum
  - APFEL DGLAP+QED as used by NNPDF2.3 [V. Bertone et al.] https://apfel.hepforge.org/
  - plan to add NLO QED, interface APPLGRID to SANC https://apfel.hepforge.org/mela.html



[Plots produced by R. Sadykov and V. Bertone]

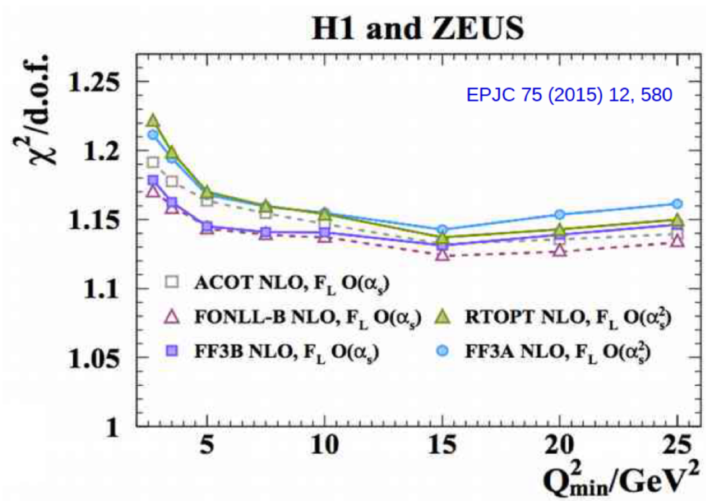
Perfect agreement between QEDEVOL and APFEL

- **NLO QCD + QED via APFEL in xFitter:**
  - implementing the $O(\alpha\alpha_S)$ and the $O(\alpha^2)$ corrections to the DGLAP splitting functions on top of the $O(\alpha)$ ones
  - implementing $O(\alpha\alpha_S^2)$ and the $O(\alpha^2)$, $O(\alpha^2\alpha_S)$ corrections to β functions
  - when including NLO QED corrections, not only the evolution is affected but also the DIS structure functions

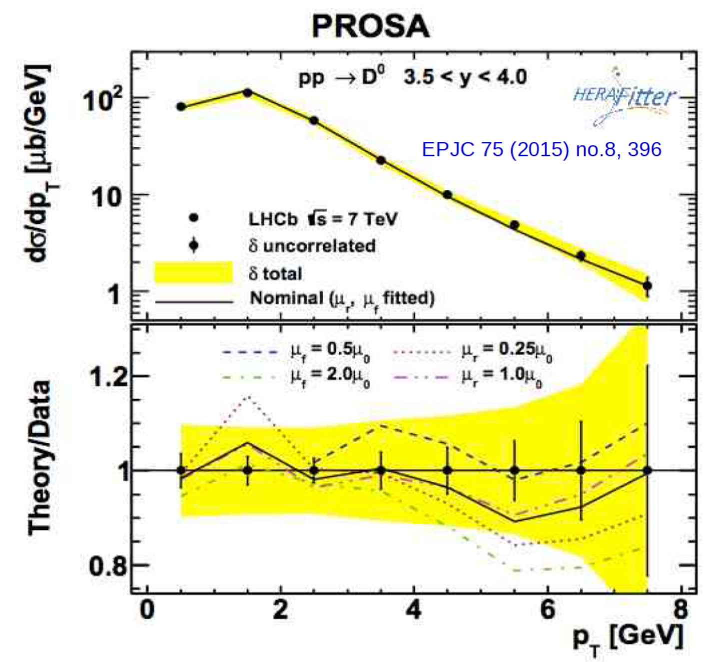


Physics cases in xFitter (2)

- Addition of new Heavy Flavour Scheme: **FONLL VFNS**
  - it is available thanks to collaboration with APFEL
  - various FONLL options available via interface to APFEL https://apfel.hepforge.org/
  - ABM scheme was up-to-dated to OPENQCDRAD v2.0b4 http://www-zeuthen.desy.de/~alekhin/OPENQCDRAD



- **Interface to Mangano-Nason-Ridolfi** (MNR, NPB 373 (1992) 295) theory code added in xFitter:
  - was used for analysing the heavy-flavour production at
  - LHCb and at HERA (via OPENQCDRAD)
  - use of FFNS for accounting of heavy quark masses at NLO
  - added corresponding LHCb data



- **Added extra reweighing option** using Giele-Keller weights

Release strategy

- Frozen Frog: 2.0.0 is two years old → new release out (relatively) soon! ☺
- Main new feature: modular, developer friendly procedure to add new reactions (based on C++)
- Tools for automatic creation of the template implementation (and some new reactions added)
- More modular code structure: alternative minimization, evolution, easier parametrisation
- Easier extension of xFitter for nuclear fits, QCD+EW fits
- Developers' team is testing this new release intensively
- Feedback from users really welcome → **xfitter-help@desy.de**

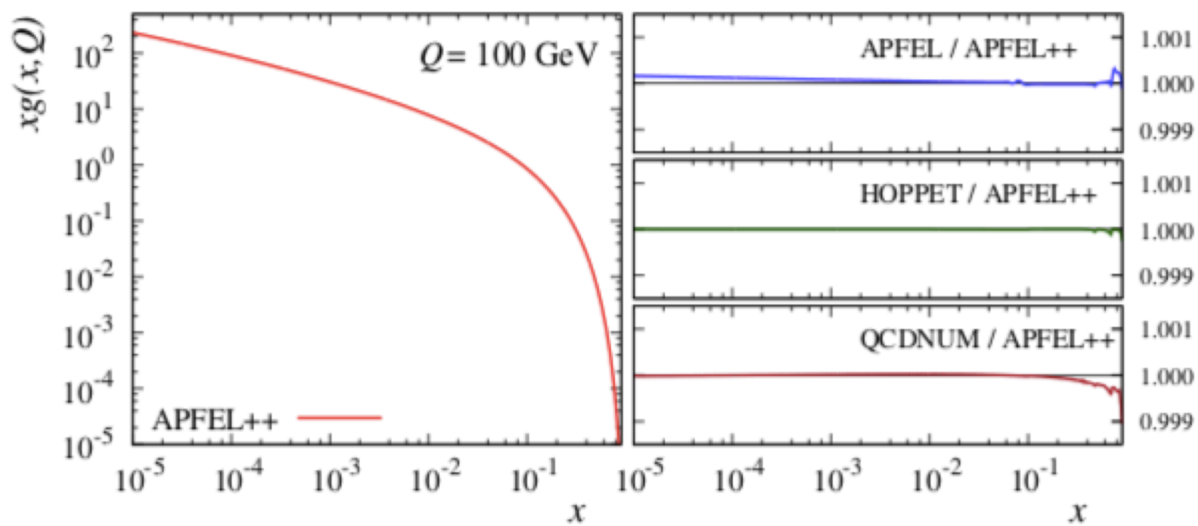
Code developments: APFEL++

- Main application field is **collinear/TMD factorisation**
- Relevant quantities computed as convolutions:

$$M(x) = \int_x^1 \frac{dy}{y} O(y) d\left(\frac{x}{y}\right) = \int_x^1 \frac{dz}{z} O\left(\frac{x}{z}\right) d(z) \equiv O(x) \otimes d(x)$$

O: complicated object slow to compute e.g. perturbative hard cross section
d: a fast-to-access function e.g. non-perturbative PDF

- The purpose is to make convolution fast
- Doxygen documentation
- Several NNLO applications:
  - DGLAP evolution
  - DIS structure function
- Really fast in performing PDF evolution



Code developments: APFEL++

- New functionalities:
  - Semi-Inclusive DIS (SIDIS) in collinear factorisation
  - TMD phenomenology:
    - evolution and matching
    - DY and SIDIS q_T distributions
  - Transversity distributions (PDFs and FFs)

- In SIDIS, what enters the computations of the cross section is:

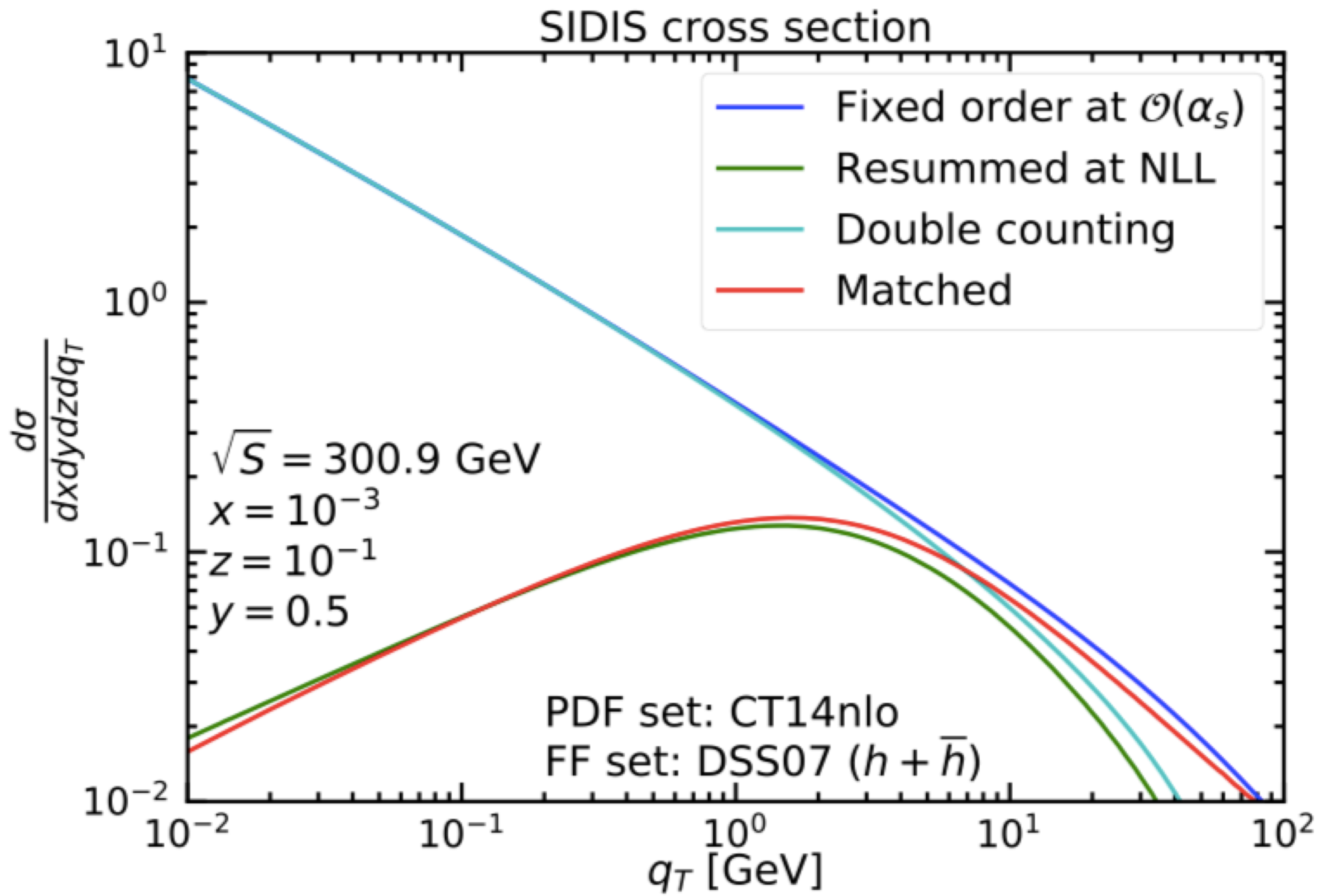
$$\mathcal{L}_{\rm SIDIS} = \int \frac{d^2\mathbf{b}_T}{(2\pi)^2} e^{-i\mathbf{q}_T\cdot\mathbf{b}_T} F_{f/P}(x,\mathbf{b}_T;\mu,\zeta_F) D_{H/f}(x,\mathbf{b}_T;\mu,\zeta_D)$$

Fourier transform — PDFs — FFs

- APFEL provides the ideal environment for this computation:
  - fast and accurate interpolation techniques
  - precomputation of the time consuming bits

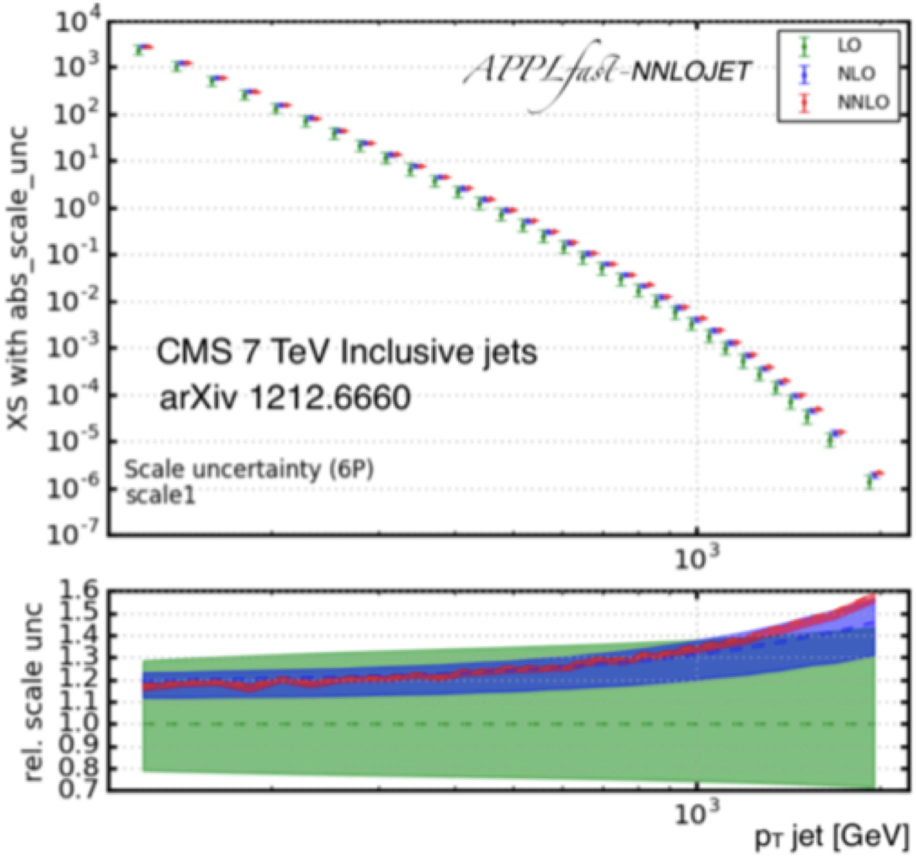
Code developments: APFEL++

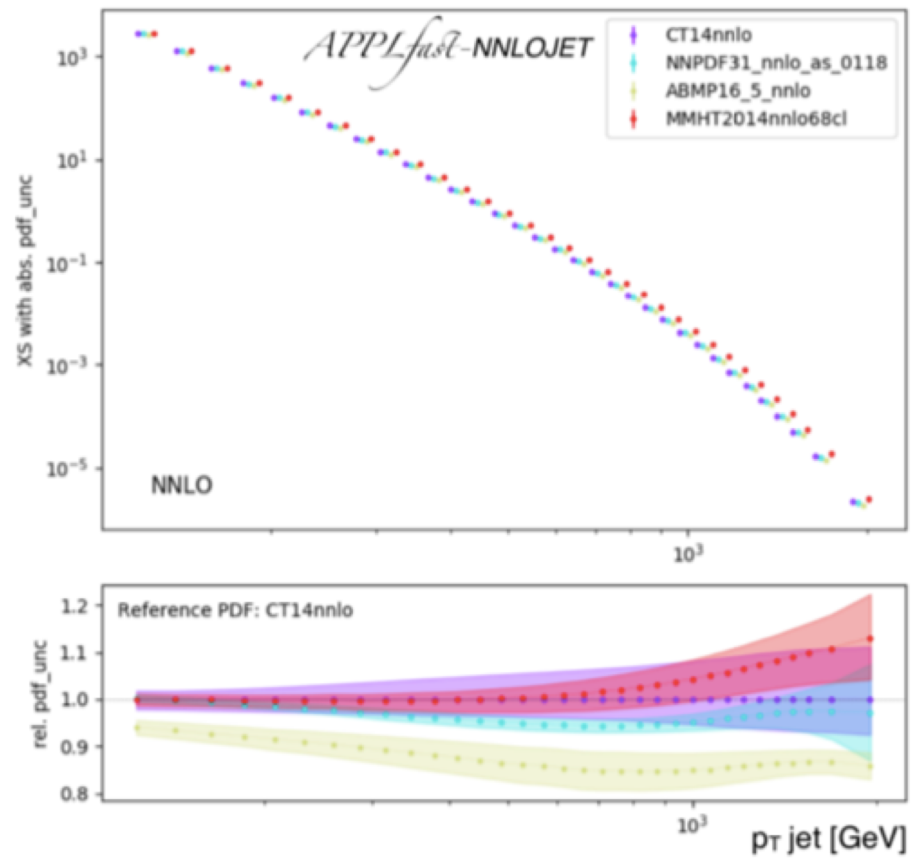
- Matching collinear and TMDs regime:



Code developments: NNLOjet

- NNLOjet grids can be used within xFitter framework





- PDF error determinations and PDF fits reasonably fast
- Scale variations vary fast for all scale-variations concepts

Code developments: NNLOjet

- NNLO grids production is ongoing

- **ep → jets:**
  - Grids for all inclusive-jet and dijet cross sections at HERA available (public ~spring 2019)

- **pp → jets:**
  - Grids are being produced
  - First full stat. grids are currently validated e.g. scale variations, closure of NNLOJET calculations
  - Low-stat. grids publically available (feedback needed)

- **pp → anything else (Z,Z+jets,…):**
  - Grids can be produced on request

- Ploughshare may be used for distribution of grids http://ploughshare.web.cern.ch

What's the aim of our work?

- We want to fit the HERAI+II inclusive cross section including **small-x resummation** corrections up to **NLLx**:
  - Resummed PDF evolution
  - Resummed DIS structure functions
  - Resummed PDF matching conditions
- Resummation corrections are properly matched to the fixed-order (FO) expressions:
  - FO components provided by **APFEL** (by V. Bertone, S. Carrazza, J. Rojo) – https://github.com/scarrazza/apfel **Comput.Phys.Commun. 185 (2014) 1647-1668**
  - Resummed corrections available in **HELL** (by M. Bonvini, et al.) – https://www.ge.infn.it/~bonvini/hell/ **JHEP 1712 (2017) 117**
    - They include both massless and massive coefficient functions
  - Implementation of the **FONLL heavy-quark scheme** with small-x corrections

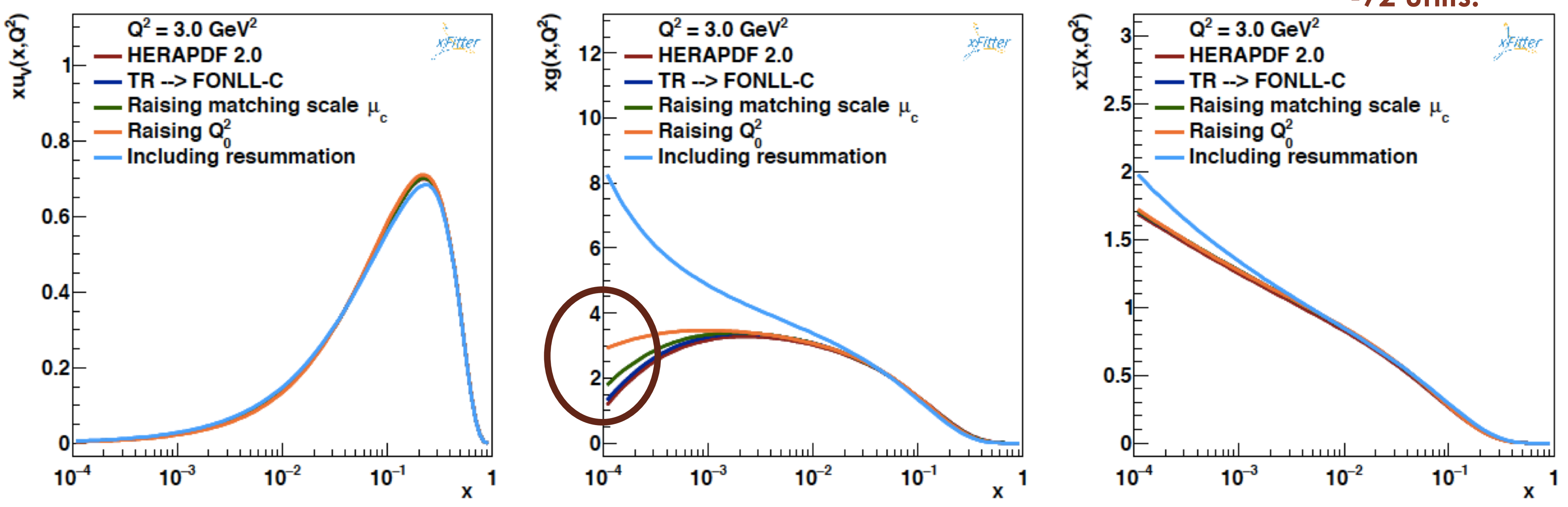
Fit setup

- The aim is to move in small steps from the HERAPDF2.0 NNLO setup (Step-1) to a setup with small-x resummed corrections with APFEL+HELL:
  - Step-2: use FONLL-C instead of TR (required to use APFEL)
  - Step-3: raise the charm matching scale $\mu_c = 1.12 \cdot m_c \simeq 1.6$ GeV ($m_c = 1.43$ GeV)
  - Step-4: move up Q_0 (required to use HELL) - $Q_0^2 = 2.56$ GeV^2
  - Step-5: add small-x resummation at NLLx

EPJC 77 (2017) 837

	Step-1	Step-2	Step-3	Step-4	Step-5
	HERAPDF2.0 NNLO	RT→FONLL-C	raise the charm matching scale μ_c	raise the initial scale Q_0	include NLLx resummation
HERA χ^2/d.o.f.	1363/1131	1387/1131	1390/1131	1388/1131	1316/1131

-72 units!



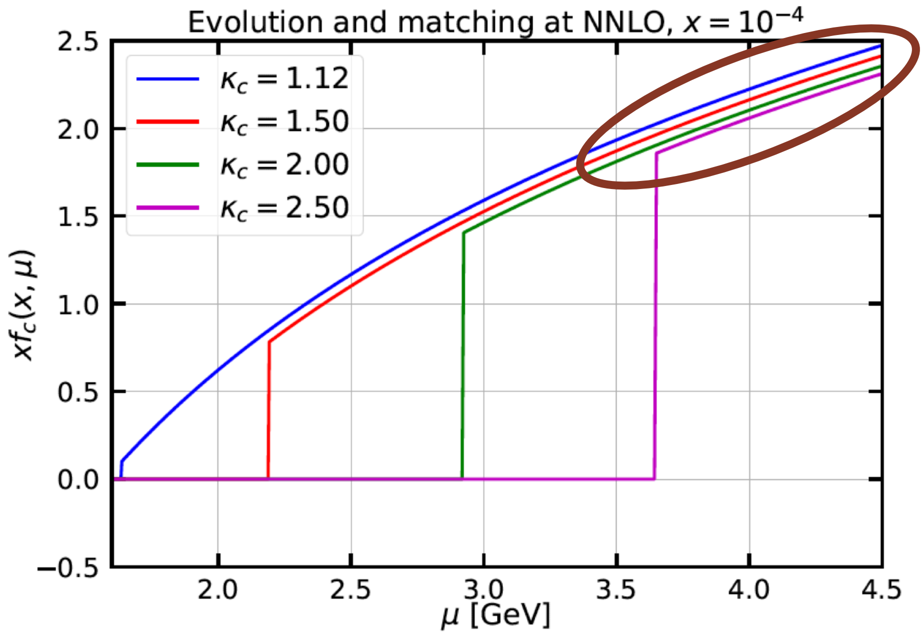
χ^2 definition

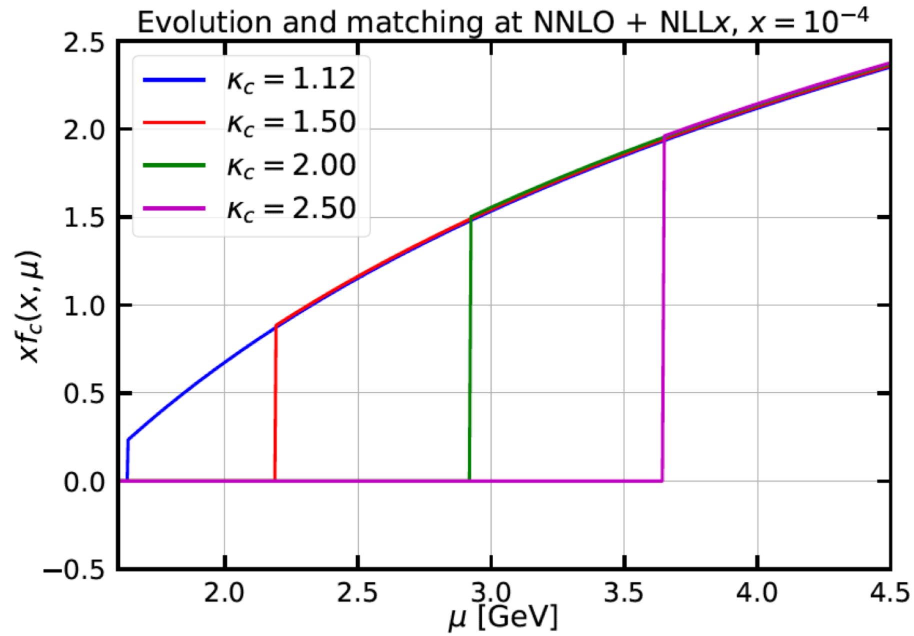
$$\chi^2 = \underbrace{\sum_i \frac{\left[D_i - T_i\left(1 - \sum_j \gamma_j^i b_j\right)\right]^2}{\delta_{i,\mathrm{unc}}^2 T_i^2 + \delta_{i,\mathrm{stat}}^2 D_i T_i}}_{\tilde{\chi}^2} + \underbrace{\sum_j b_j^2}_{\mathbf{corr}} + \underbrace{\sum_i \ln \frac{\delta_{i,\mathrm{unc}}^2 T_i^2 + \delta_{i,\mathrm{stat}}^2 D_i T_i}{\delta_{i,\mathrm{unc}}^2 D_i^2 + \delta_{i,\mathrm{stat}}^2 D_i^2}}_{\mathbf{log}}$$

- First term: Data description (partial χ^2)
  - γ_j^i = Correlated systematic uncertainties
  - b_j = Correlated systematic uncertainties shifts
- Second term: Correlated term
  - Reduction of this term indicates that the fit does not require the predictions to be shifted so far within the tolerance of the systematic uncertainties
- Third term: Log penalty term
  - Reduction of this term reflects a better agreement of the theoretical predictions (T_i) with the data (D_i)

PDF matching conditions

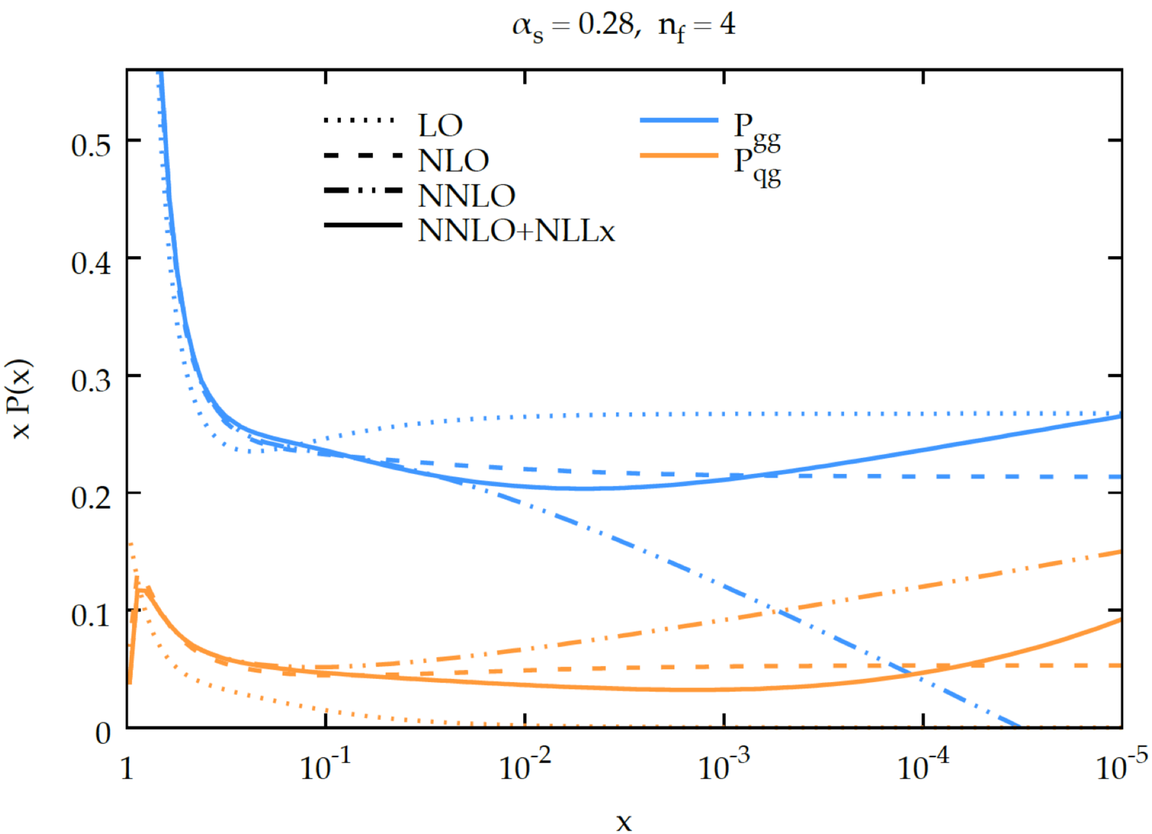
- Also the PDF matching conditions are affected by large logs in the low-x region
- These logs are resummed in HELL





- Charm PDF at x = 10^{-4} as a function of the factorisation scale μ for different values of the charm matching scale $\boldsymbol{\mu_c = \kappa_c \cdot m_c}$ (with m_C = 1.43 GeV)
- Moving forward the charm matching scale (FO) → **depressed charm PDF** (which needs to be compensated by increased gluon)
  Origin of the difference in the gluon PDF at small-x at Step-3 (previous slide)
- Reduced μ_c dependence when resummation included

Splitting functions



Splitting functions for $\mathbf{xP_{gg}(x)}$ and $\mathbf{xP_{qg}(x)}$ at:

- LO (dotted)
- NLO (dashed)
- NNLO (dot-dot-dashed)
- NNLO + NLLx (solid)

$Q^2 \sim 4$ GeV^2

At NNLO $xP_{gg}(x) \rightarrow -\infty$ when $x \rightarrow 0$ → **UNPHYSICAL**

NLLx small correction wrt NLO (better perturbative stability)

- From NLO → NNLO: logs contribution visible and perturbative instability
- At pure NNLO, $xP_{gg}(x)$ falls for $x \rightarrow 0$ with $xP_{qg}(x) > xP_{gg}(x)$ for $x \lesssim 10^{-3}$
- When resummation is added:
  - Relation $xP_{qg}(x) < xP_{gg}(x)$ restored
  - **Gain in perturbative stability**

Charm PDF

- The aim is to move in small steps from the HERAPDF2.0 NNLO setup (Step-1) to a setup with small-x resummed corrections with APFEL+HELL:
  - Step-2: use FONLL-C instead of TR (required to use APFEL)
  - Step-3: raise the charm matching scale $\mu_c = 1.12 \cdot m_c \simeq 1.6$ GeV ($m_c = 1.43$ GeV)
  - Step-4: move up Q_0 (required to use HELL) - $Q_0^2 = 2.56$ GeV^2
  - Step-5: add small-x resummation at NLLx

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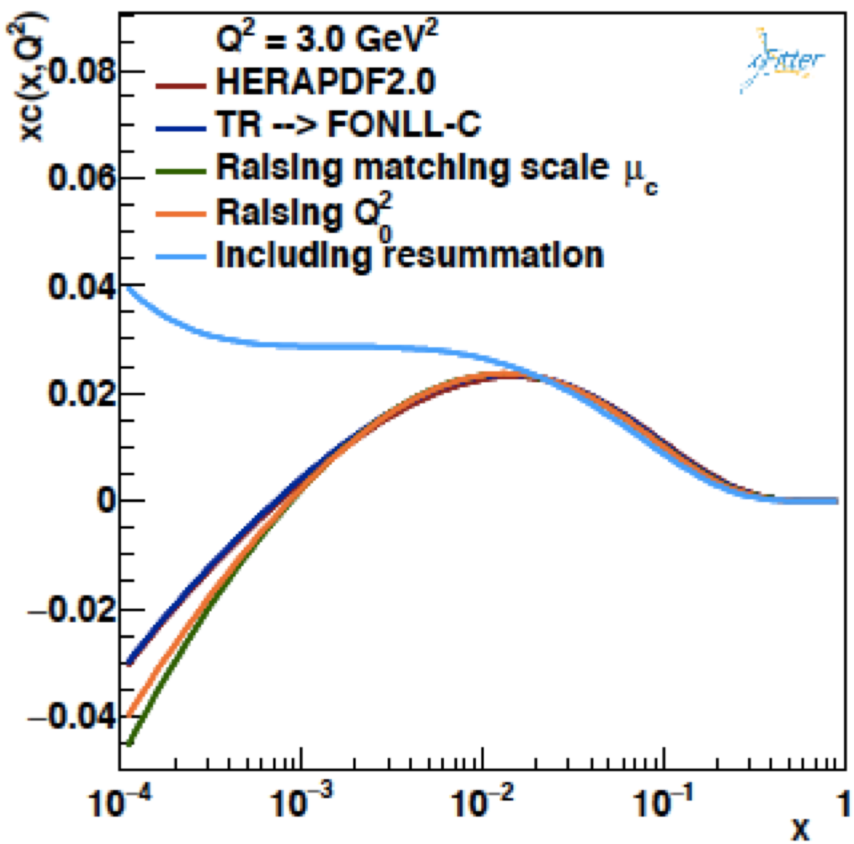
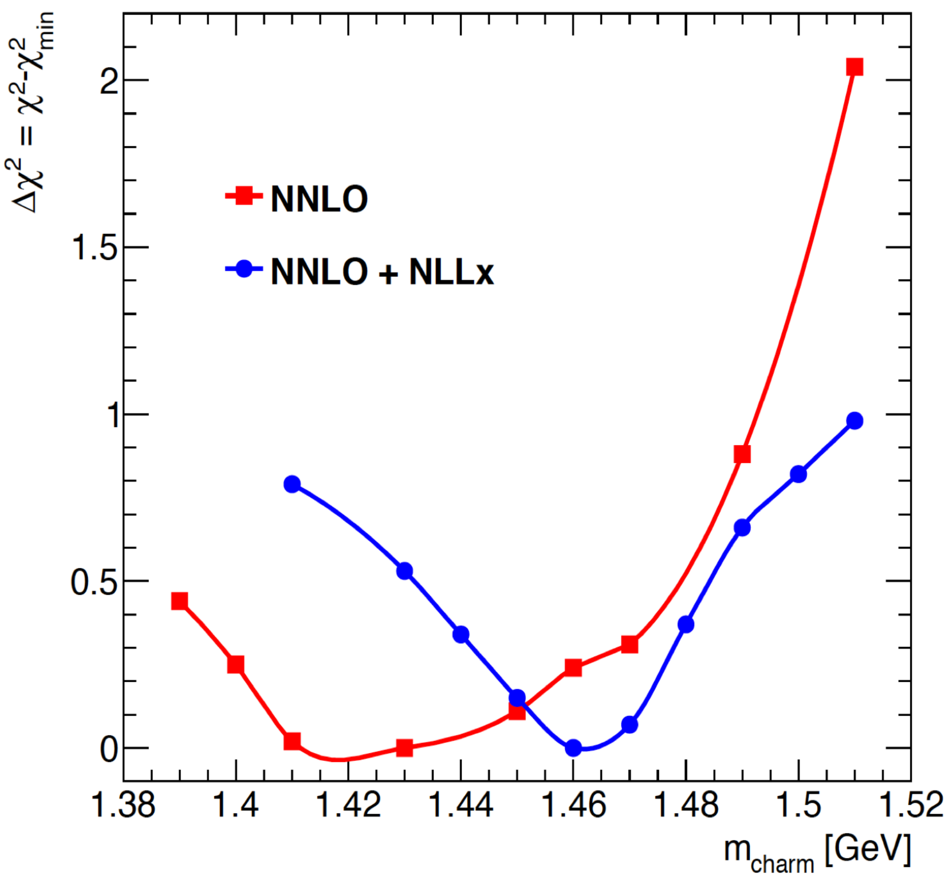
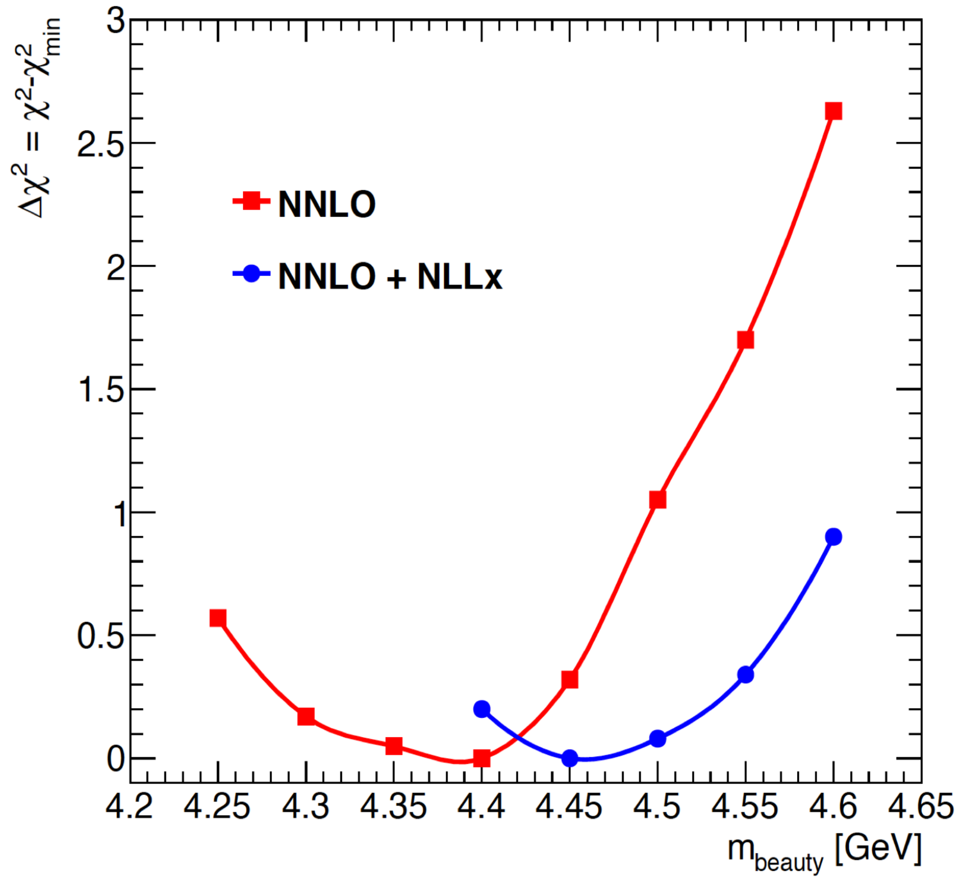


Optimal m_c and m_b values for the fit

Heavy flavour mass scheme: **FONLL-C with/without small-x corrections included**

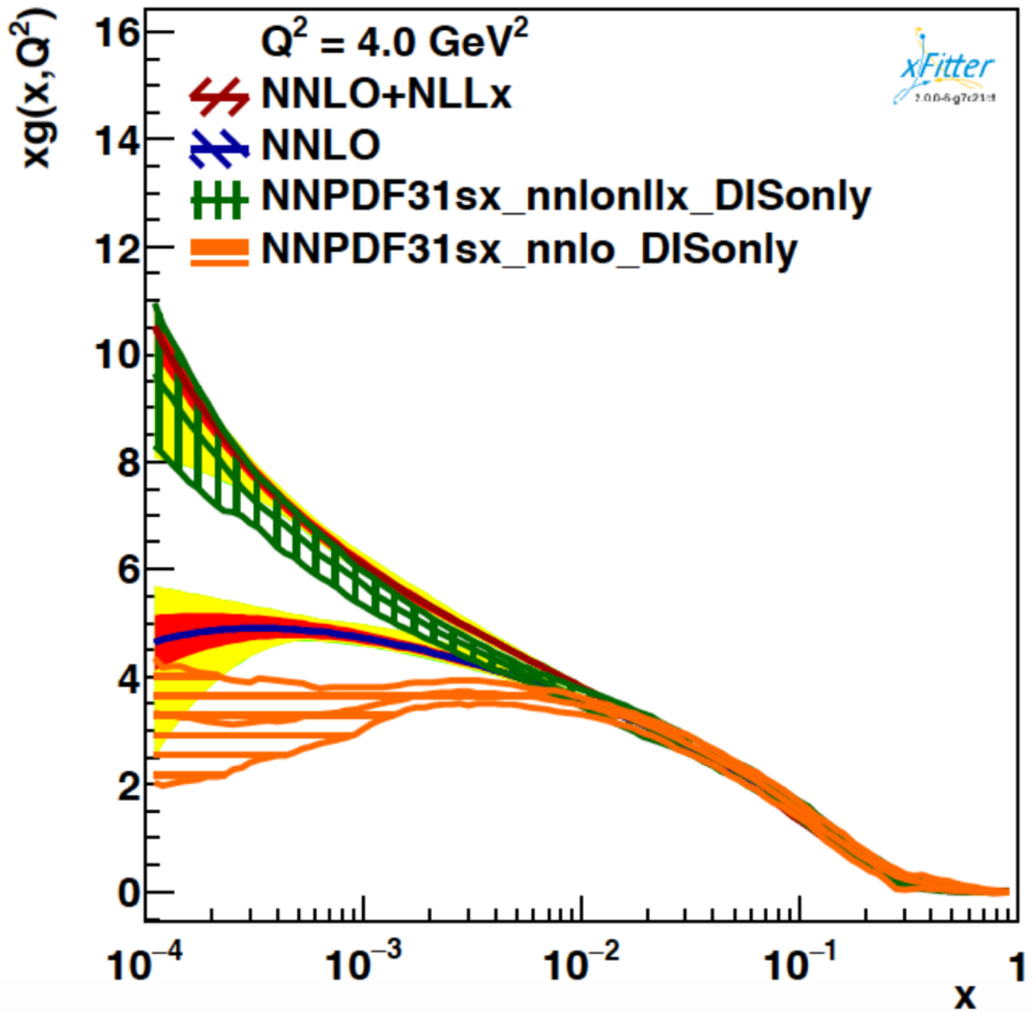


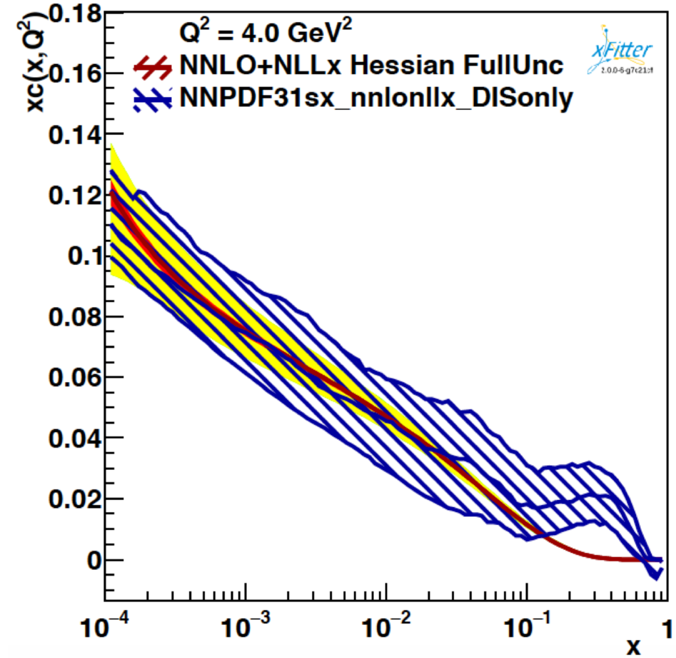
N.d.f = 1178

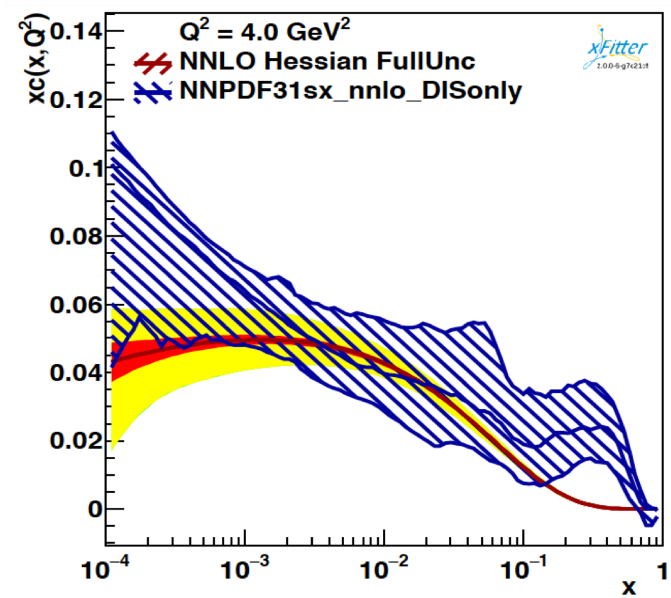


N.d.f = 1207

Comparison with NNPDF31 sets







- **Bigger difference at NNLO due to a bigger difference in the charm PDF**

More detailed comparison to NNPDF31

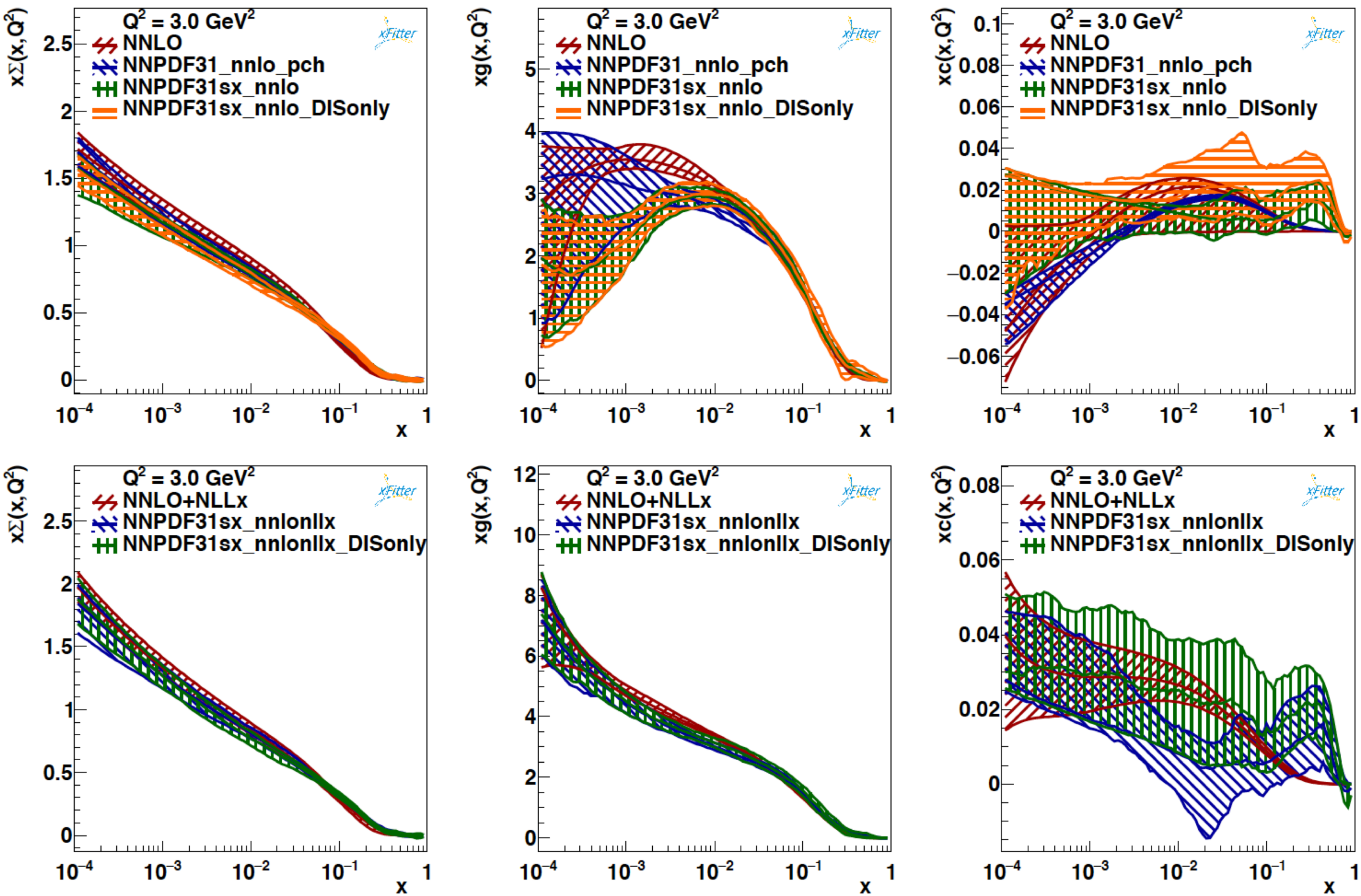
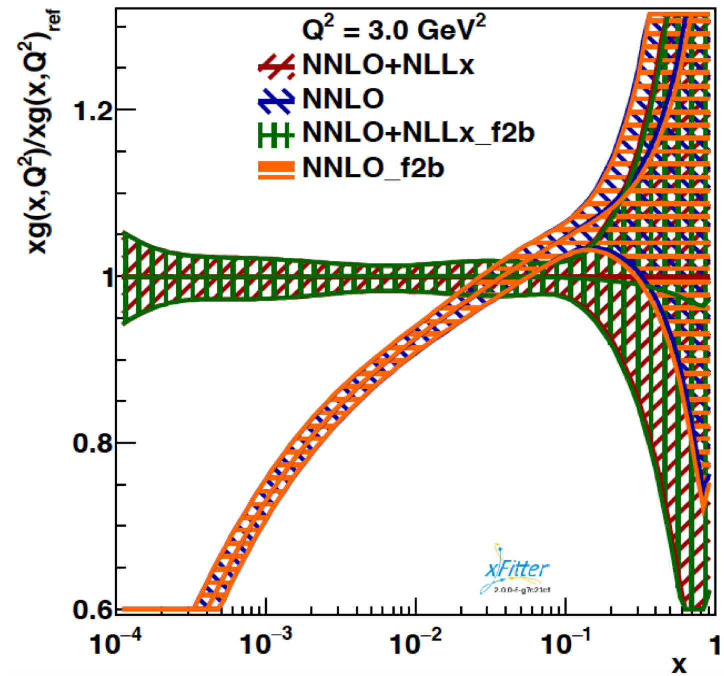


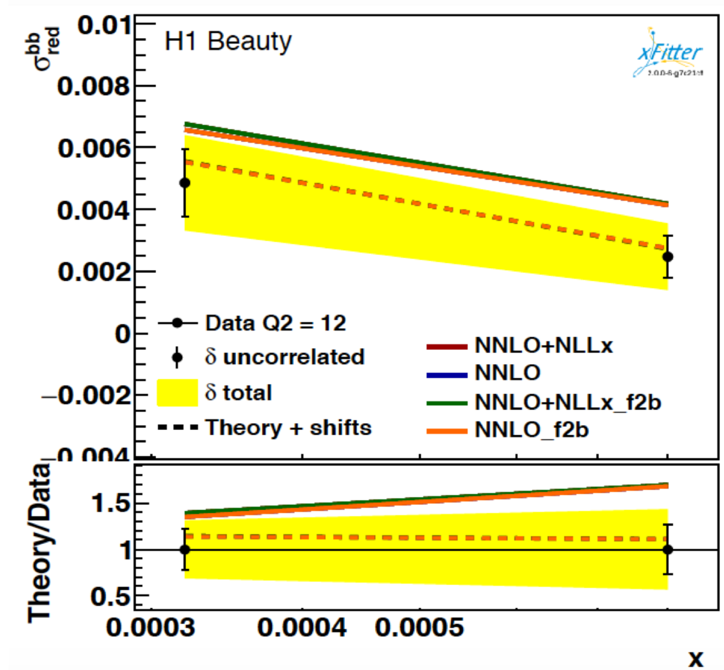
Figure 9 The total singlet, gluon and charm PDFs for the final fits at NNLO (upper plots) and NNLO+NLLx (lower plots) compared to the analogous NNPDF3.1 determinations.

H1 F_2 beauty data

- We included the H1 F_2 beauty data in our fit
- Scan to identify the optimal m_b mass in the FONLL-C mass scheme with NLLx resummation:
  - m_b = 4.40 GeV —> 1393.95/1207 (1.162)
  - m_b = 4.45 GeV —> 1393.75/1207 (1.162)
  - m_b = 4.50 GeV —> 1393.83/1207 (1.162)
  - m_b = 4.55 GeV —> 1394.09/1207 (1.162)
  - m_b = 4.60 GeV —> 1394.65/1207 (1.163)
- **m_c = 1.46 GeV** (optimal value for FONLL-C)
- Fit pretty insensitive to this variation so we stuck to our nominal choice (**m_b = 4.50 GeV**)

Dataset	NNLO+NLLx	NNLO	NNLO+NLLx f2b	NNLO f2b
Beauty cross section ZEUS Vertex	-	-	13 / 17	13 / 17
Charm cross section H1-ZEUS combined	50 / 47	47 / 47	50 / 47	47 / 47
HERA1+2 CCep	45 / 39	43 / 39	45 / 39	43 / 39
HERA1+2 CCem	53 / 42	57 / 42	53 / 42	57 / 42
HERA1+2 NCem	223 / 159	215 / 159	223 / 159	215 / 159
HERA1+2 NCep 820	65 / 70	67 / 70	65 / 70	67 / 70
HERA1+2 NCep 920	413 / 377	447 / 377	413 / 377	447 / 377
HERA1+2 NCep 460	222 / 204	217 / 204	222 / 204	217 / 204
HERA1+2 NCep 575	217 / 254	219 / 254	217 / 254	219 / 254
H1 F2 Beauty no shift	-	-	3.4 / 12	3.5 / 12
Correlated χ^2	89	116	91	119
Log penalty χ^2	-4.80	+19	-1.86	+22
Total χ^2 / dof	1373 / 1178	1446 / 1178	1394 / 1207	1468 / 1207
χ^2 p-value	0.00	0.00	0.00	0.00





Log term inclusive and log term charm

Standard **NNLO+NLLx vs NNLO fits** (w/o $Q^2 = 2.7$ GeV^2 bin)

After minimisation 1372.98 1178 1.166

Partial chi2s

413.12(+5.07)	377	HERA1+2 NCep 920
65.25(-0.56)	70	HERA1+2 NCep 820
216.96(-1.46)	254	HERA1+2 NCep 575
221.66(-3.44)	204	HERA1+2 NCep 460
223.20(-0.87)	159	HERA1+2 NCem
45.53(+0.52)	39	HERA1+2 CCep
53.61(-2.43)	42	HERA1+2 CCem
49.50(-1.06)	47	Charm cross section

Correlated Chi2 88.382726246930133
Log penalty Chi2 -4.2267289601319771

HERAonly:
77.0 to the correlated chi2;
-2.9 to the log penalty term
charm data:
11.4 to the correlated chi2;
1.3 to the log penalty term

After minimisation 1445.55 1178 1.227

Partial chi2s

445.57(+13.03)	377	HERA1+2 NCep 920
66.82(+0.99)	70	HERA1+2 NCep 820
218.39(+3.93)	254	HERA1+2 NCep 575
216.46(+1.39)	204	HERA1+2 NCep 460
215.07(+1.63)	159	HERA1+2 NCem
43.50(+0.86)	39	HERA1+2 CCep
56.84(-1.57)	42	HERA1+2 CCem
47.47(-1.50)	47	Charm cross section

Correlated Chi2 116.69776308230242
Log penalty Chi2 18.750060129311155

HERAonly:
101.7 to the correlated;
20.4 to the log penalty term
charm data:
15.0 to the correlated chi2;
-1.7 to the log penalty term

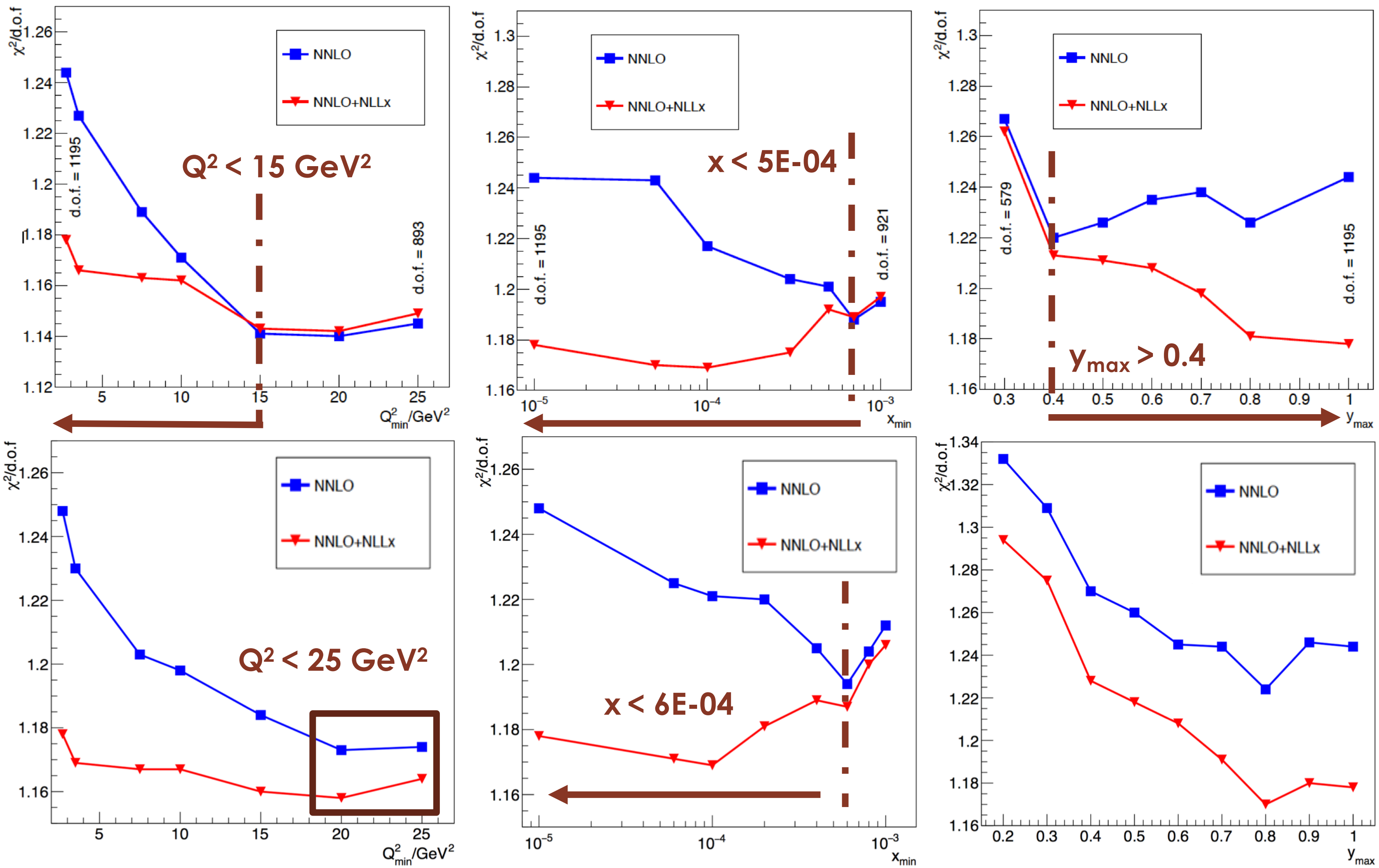
Q^2, x_{min} and y_{max} scans

We tried to identify the region where resummation is important:

- Refitting with different cuts on Q^2, x_{min} and y_{max}
- Recomputing χ^2 just varying the cuts on Q^2, x_{min} and y_{max}

Refitting

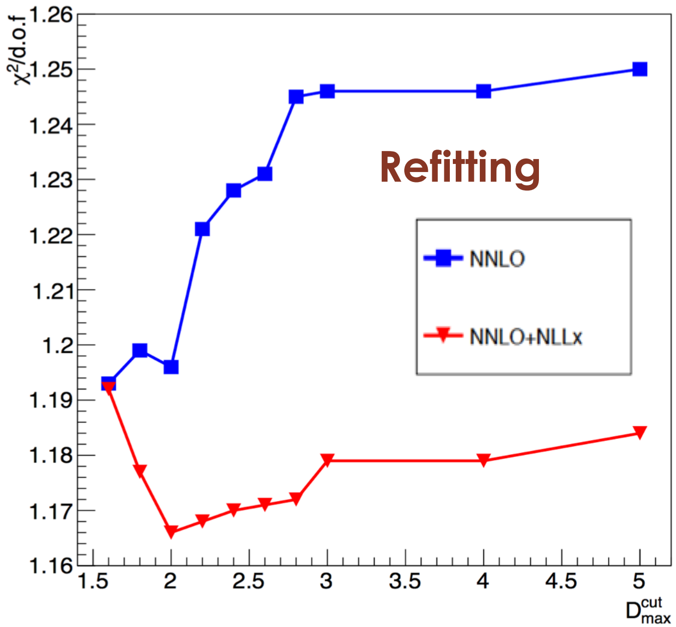
χ^2 varying the cuts

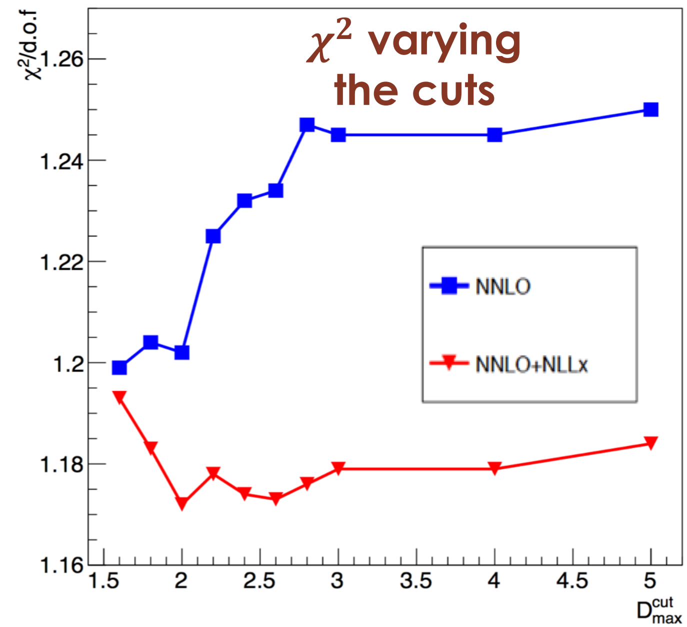


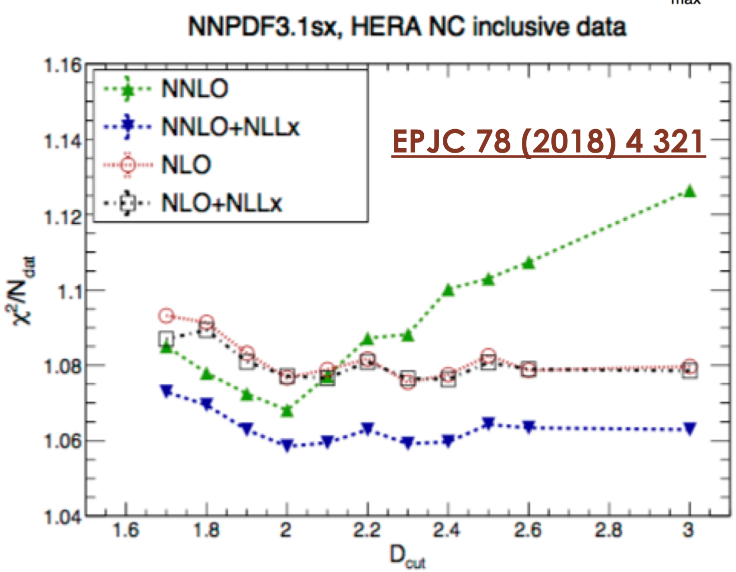
Simultaneous cut on x and Q^2

Simultaneous cut on Q^2 and x implemented: $\ln(1/x) \geq \beta_0 D_{cut} \ln(Q^2/\Lambda^2)$ where $\Lambda \cong 88\ MeV$

$\beta_0 \cong 0.61$



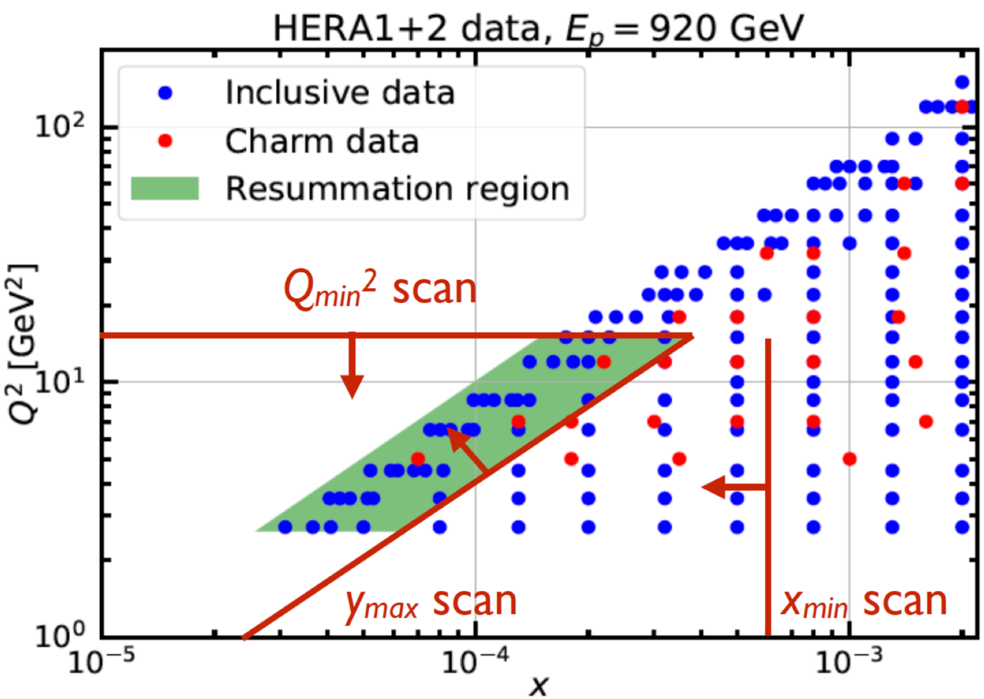




Consistent with what has been found in the NNPDF paper:

- $D_{cut} > 2$ defines the region where resummation is important
- Flat-ish χ^2 distribution for NNLO+NLLx
- Above $D_{cut} = 3$ few data points added even if with huge steps

Region where resummation has a significant effect



Defined by:
- $x < 5 \cdot 10^{-4}$
- $2.7 < Q^2 < 15$ GeV^2
- $0.4 < y < 1.0$

- χ^2 scans have obtained independently from one another - **our estimate reliable?**
- Two additional fits, w/wo resummation, excluding only the data points in the green area
- The total χ^2's of these fits differ by ~15 units in favour of the resummed fit (mostly due to the correlated and logarithmic terms)
- To be compared to the 74 units of when the shaded area is instead included (region corresponds to where low-Q^2 F_L structure function contributes the most)
- This confirms that the shaded area provides **a reliable estimate of the kinematic region in which resummation works significantly better than fixed order**

Region where resummation has a significant effect

——— NNLO+NLLx ———			——— NNLO ———		
After minimisation	1249.201064 1.174		After minimisation	1264.22 1064 1.188	
Partial chi2s			Partial chi2s		
395.95(+3.95)	354	HERA1+2 NCep 920	402.82(+7.25)	354	HERA1+2 NCep 920
51.32(-0.64)	56	HERA1+2 NCep 820	52.23(-0.10)	56	HERA1+2 NCep 820
179.52(-1.09)	214	HERA1+2 NCep 575	177.53(+1.15)	214	HERA1+2 NCep 575
179.12(-2.25)	170	HERA1+2 NCep 460	176.67(-0.31)	170	HERA1+2 NCep 460
222.78(-0.82)	159	HERA1+2 NCem	215.44(+1.04)	159	HERA1+2 NCem
45.59(+0.57)	39	HERA1+2 CCep	44.30(+0.35)	39	HERA1+2 CCep
53.88(-2.45)	42	HERA1+2 CCem	54.93(-1.58)	42	HERA1+2 CCem
44.53(-1.11)	44	Charm cross section	45.39(-1.31)	44	Charm cross
Correlated Chi2	80.329061352348674		Correlated Chi2	88.418716117383113	
Log penalty Chi2	-3.8395890369565198		Log penalty Chi2	6.4854418695532452	

- The total χ^2's of these fits differ by around 15 units in favour of the resummed fit, mostly due to the correlated and logarithmic terms, to be compared to the 73 units of when the shaded area is instead included.
- This confirms that, the context of DIS, the shaded area in Fig. 11 does provide a reliable estimate of the kinematic region in which resummation works significantly better than fixed order.

Adding the negative gluon term

Do we really need the negative term of gluon? → We produced a version of the **final NNLO+NLLx and NNLO fits without the negative term** just to check this

NNLO+NLLx (standard)

2	'Bg'	-0.074490	0.022636
3	'Cg'	7.039247	0.795647
7	'Aprig'	-0.000320	0.000114
8	'Bprig'	-0.980215	0.017543
9	'Cprig'	25.000000	0.000000
12	'Buv'	0.745665	0.028726
13	'Cuv'	4.959985	0.083442
15	'Euv'	11.636086	1.515132
22	'Bdv'	0.918106	0.089333
23	'Cdv'	4.650377	0.401623
33	'CUbar'	7.607920	1.258096
34	'DUbar'	4.361805	2.421517
41	'ADbar'	0.242674	0.009819
42	'BDbar'	-0.172176	0.004965
43	'CDbar'	8.818216	1.769683

NNLO+NLLx (w/o neg term gluon)

2	'Bg'	-0.138521	0.011161
3	'Cg'	5.593441	0.396115
7	'Aprig'	0.000000	0.000000
8	'Bprig'	0.000000	0.000000
9	'Cprig'	0.000000	0.000000
12	'Buv'	0.754178	0.023272
13	'Cuv'	4.961712	0.082724
15	'Euv'	11.152505	1.351389
22	'Bdv'	0.944546	0.080315
23	'Cdv'	4.778010	0.382632
33	'CUbar'	7.116455	1.610122
34	'DUbar'	2.167268	2.294381
41	'ADbar'	0.263140	0.007530
42	'BDbar'	-0.161943	0.003294
43	'CDbar'	10.132906	1.891836

Similar conclusions can be drawn if considering NNLO-only term

Adding the negative gluon term

Do we really need the negative term of gluon? → We produced a version of the **final NNLO+NLLx and NNLO fits without the negative term** just to check this

NNLO (standard)

2	'Bg'	-0.073354	0.062684
3	'Cg'	6.751494	0.651243
7	'Aprig'	0.068316	0.106861
8	'Bprig'	-0.394262	0.105157
9	'Cprig'	25.000000	0.000000
12	'Buv'	0.807546	0.021963
13	'Cuv'	4.898565	0.086080
15	'Euv'	9.004091	1.152141
22	'Bdv'	1.005596	0.081207
23	'Cdv'	4.943314	0.383313
33	'CUbar'	7.002186	2.155434
34	'DUbar'	0.987550	2.682961
41	'ADbar'	0.286972	0.008839
42	'BDbar'	-0.143059	0.003815
43	'CDbar'	9.599957	1.719759

NNLO(w/o neg term gluon)

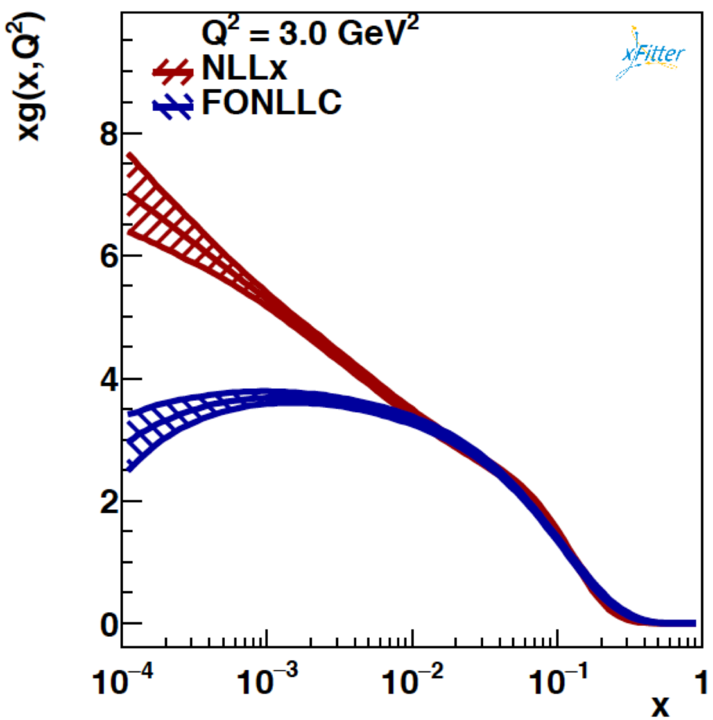
2	'Bg'	-0.004076	0.015425
3	'Cg'	7.440208	0.530265
7	'Aprig'	0.000000	0.000000
8	'Bprig'	0.000000	0.000000
9	'Cprig'	0.000000	0.000000
12	'Buv'	0.813866	0.021348
13	'Cuv'	4.894378	0.086861
15	'Euv'	8.660517	1.098470
22	'Bdv'	1.010196	0.082739
23	'Cdv'	4.970787	0.386256
33	'CUbar'	7.119678	2.129298
34	'DUbar'	1.086109	2.659349
41	'ADbar'	0.284090	0.008164
42	'BDbar'	-0.146533	0.003362
43	'CDbar'	9.315854	1.648179

Here, the output parameters for the the NNLO-only fits

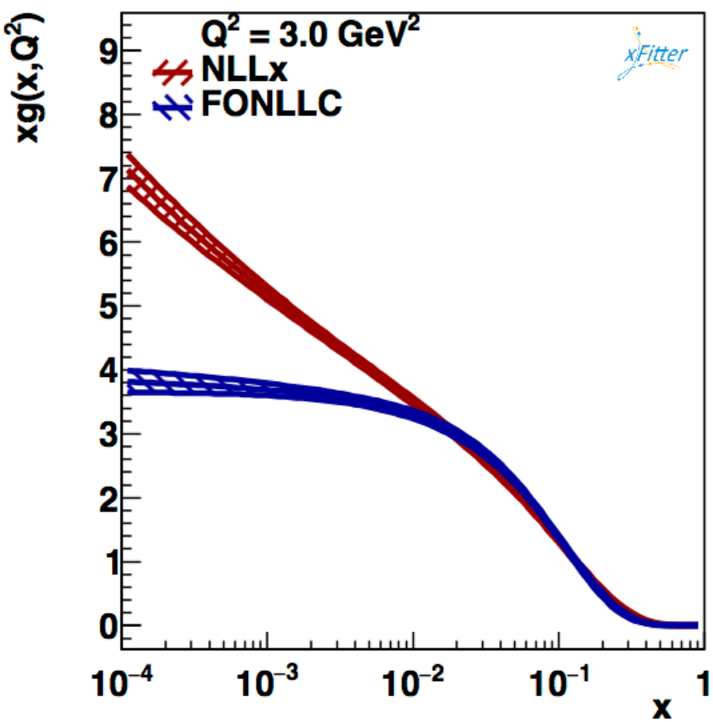
Adding the negative gluon term

Do we really need the negative term of gluon? → We produced a version of the **final NNLO+NLLx and NNLO fits without the negative term** just to check this

NNLO+NLLx (standard)



NNLO+NLLx (w/o neg term gluon)

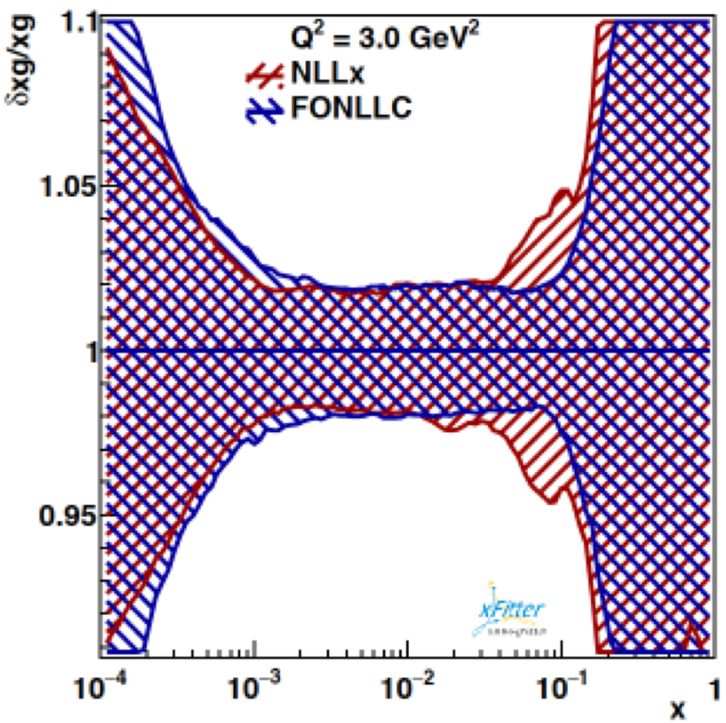


The point is that even without the negative term the gluon for NLLO likes to take a flattish shape at low-x, whereas for NNLO+NLLx it takes a singular shape

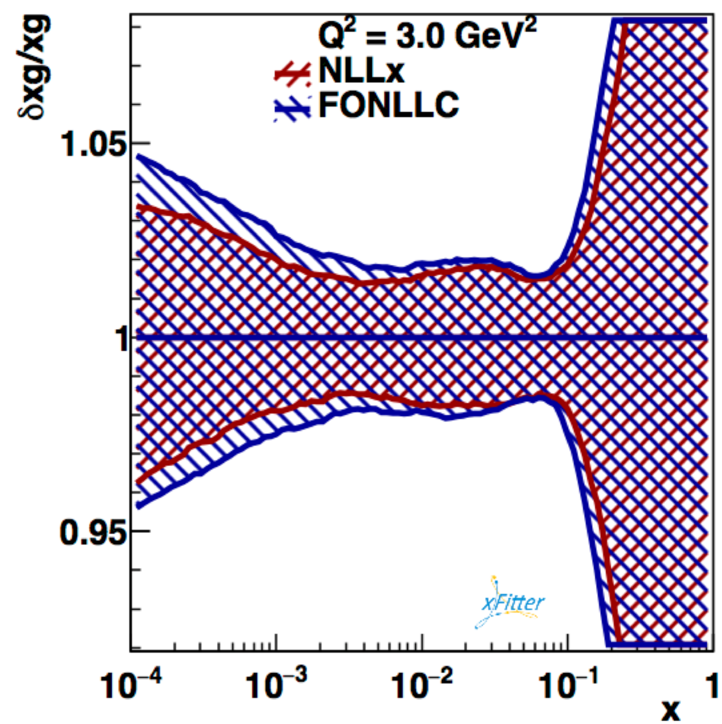
Adding the negative gluon term

Do we really need the negative term of gluon? → We produced a version of the **final NNLO+NLLx and NNLO fits without the negative term** just to check this

NNLO+NLLx (standard)



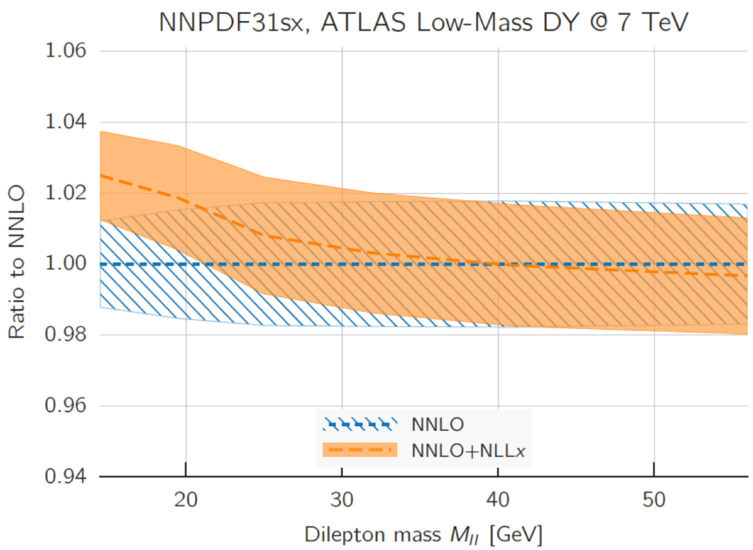
NNLO+NLLx (w/o neg term gluon)

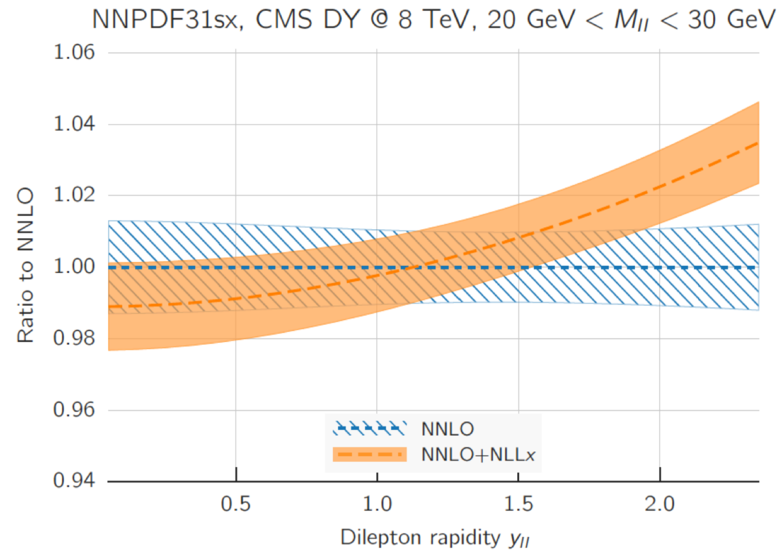


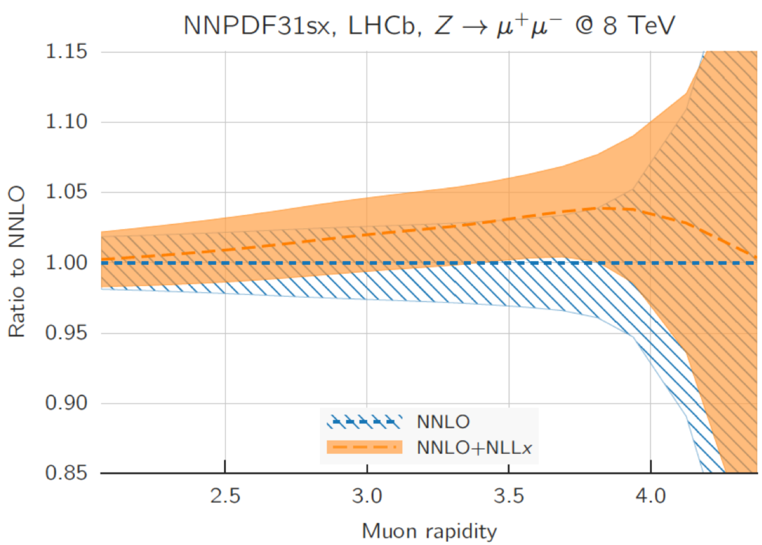
the uncertainty on the gluon PDF is lower in the low-x region for the fits without the negative term of the gluon added → probably because the gluon description is now so simple.

Impact of small-x resummation for DY process

- Possible phenomenological consequences of small-x resummation for the DY production process - EPJC 78 (2018) 4 321





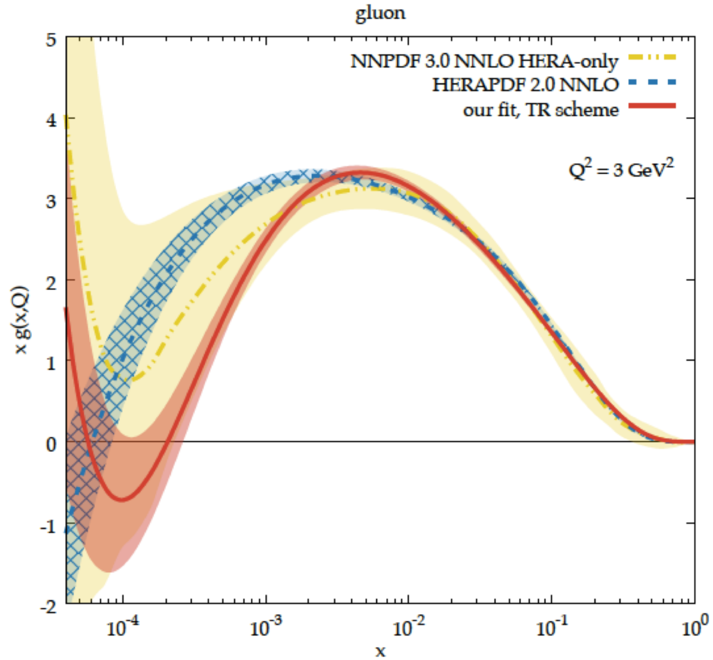


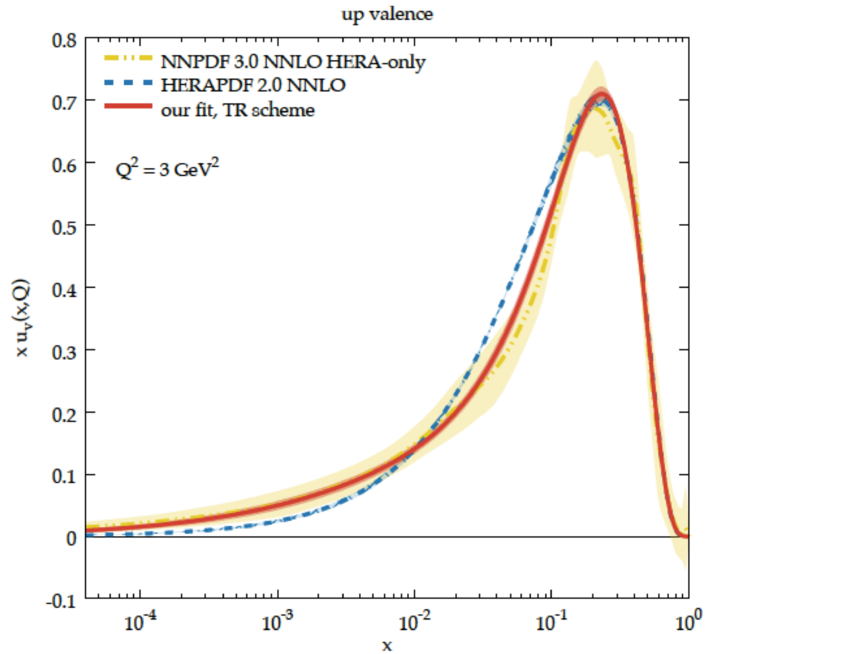
- Comparison between the NNPDF3.1sx NNLO and NNLO+NLLx predictions
- Differences are more marked for the kinematic regions directly sensitive to small-x, e.g. small m_{ll} for ATLAS data or large rapidities in the case of the CMS and LHCb measurements
- Small-x resummation included in the PDF evolution **ONLY**

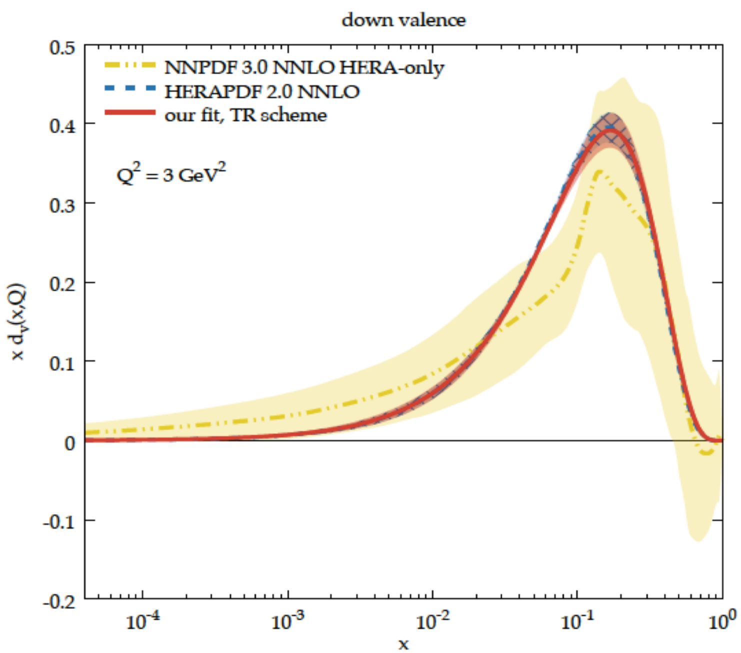
Comparison to HERAPDF2.0

Contribution to χ^2	HERAPDF2.0	Our fit (new parametrization)
subset NC e^+ 920 χ^2/n.d.p.	444/377	403/377
subset NC e^+ 820 χ^2/n.d.p.	66/70	74/70
subset NC e^+ 575 χ^2/n.d.p.	219/254	221/254
subset NC e^+ 460 χ^2/n.d.p.	217/204	222/204
subset NC e^- χ^2/n.d.p.	219/159	220/159
subset CC e^+ χ^2/n.d.p.	45/39	38/39
subset CC e^- χ^2/n.d.p.	56/42	50/42
correlation term + log term	91 + 5	75 − 3
Total χ^2/d.o.f.	**1363/1131**	**1301/1127**

$$\chi^2 = \underbrace{\sum_i \frac{\left[D_i - T_i\left(1 - \sum_j \gamma_{ij} b_j\right)\right]^2}{\delta^2_{i,\mathrm{uncor}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i}}_{\text{Exp. term}} + \underbrace{\sum_j b_j^2}_{\text{Corr. term}} + \underbrace{\sum_i \log \frac{\delta^2_{i,\mathrm{uncor}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i}{\delta^2_{i,\mathrm{uncor}} D_i^2 + \delta^2_{i,\mathrm{stat}} D_i^2}}_{\text{Log term}}$$







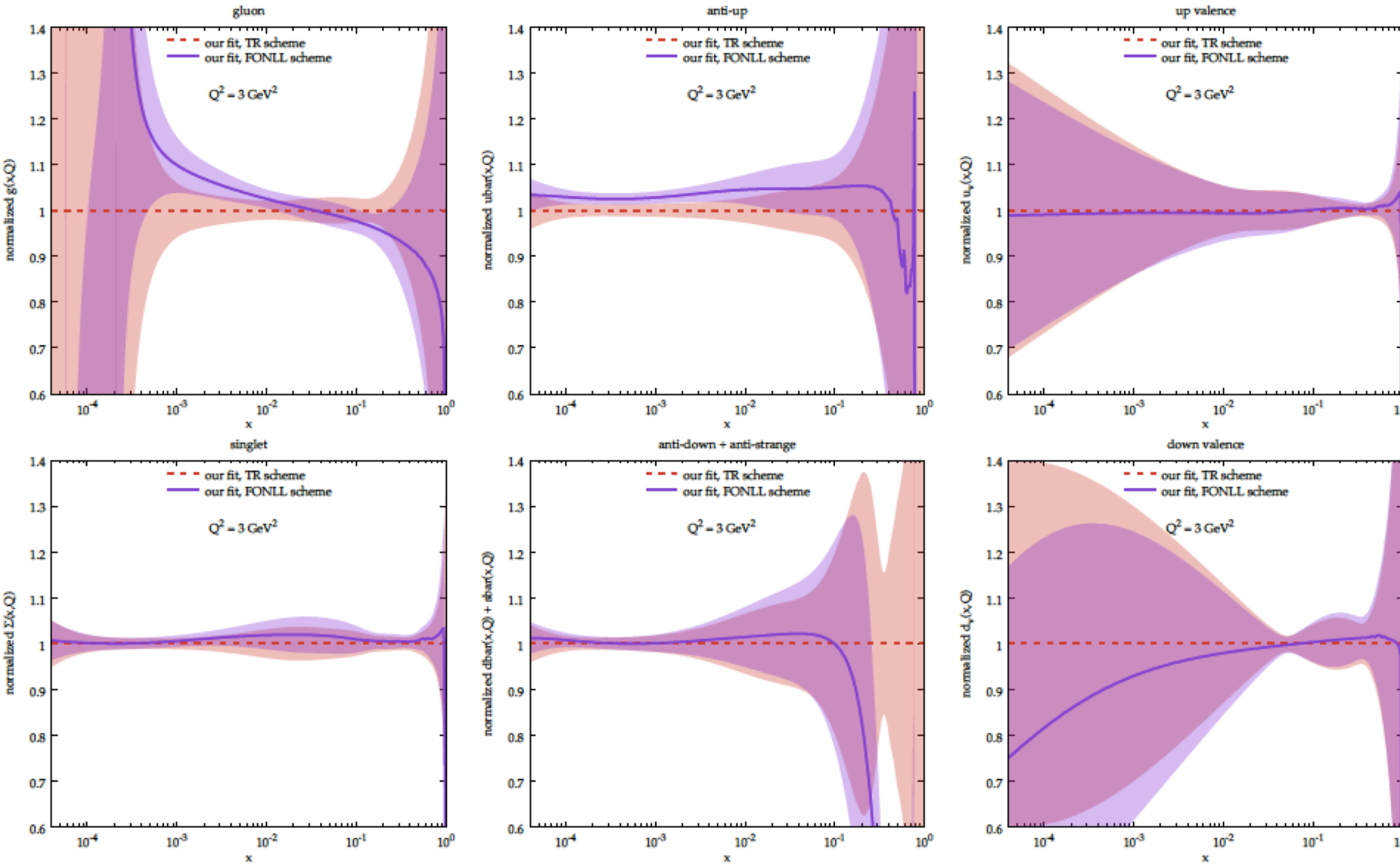
- Richer structure at medium-/high-x than HERAPDF2.0
- Gluon decreases more rapidly for $x \sim 10^{-2}$ and starts rising again for $x < 10^{-4}$
- Up-valence rather different
- Down-valence is identical (same parametrization as in HERAPDF2.0)
- If compared to NNPDF3.0 (HERA data only), qualitatively same behavior

From TR to FONLL

- Various variations studied
- First of all, migration from TR scheme to FONLL (to include small-x resummation in a later stage) – as done in Eur. Phys. J. C78 (2018) 621

Differences in the fit setup		
heavy flavour scheme	TR	FONLL
initial scale μ_0	1.38 GeV	1.6 GeV
charm matching scale μ_c	m_c	$1.12 m_c$
charm mass m_c	1.43 GeV	1.46 GeV

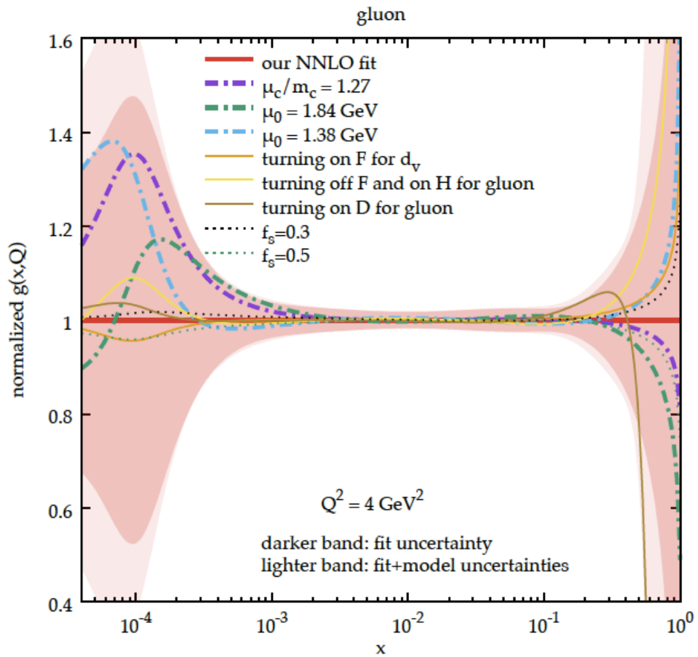
- Raising the initial scale from the HERAPDF2.0 value (Q_0^2 = 1.9 GeV^2) to Q_0^2 = 2.56 GeV^2
- FONLL scheme prefers m_c = 1.46 GeV (while m_c^{HERA} = 1.43 ± 0.06 GeV)
- The charm PDF must be generated perturbatively at a matching scale $\mu_c > \mu_0 > m_c$ which needs to be larger than the default value $\mu_c = m_c$
- So μ_c = 1.12 m_c (adopted also in Eur. Phys. J. C78 (2018) 621)



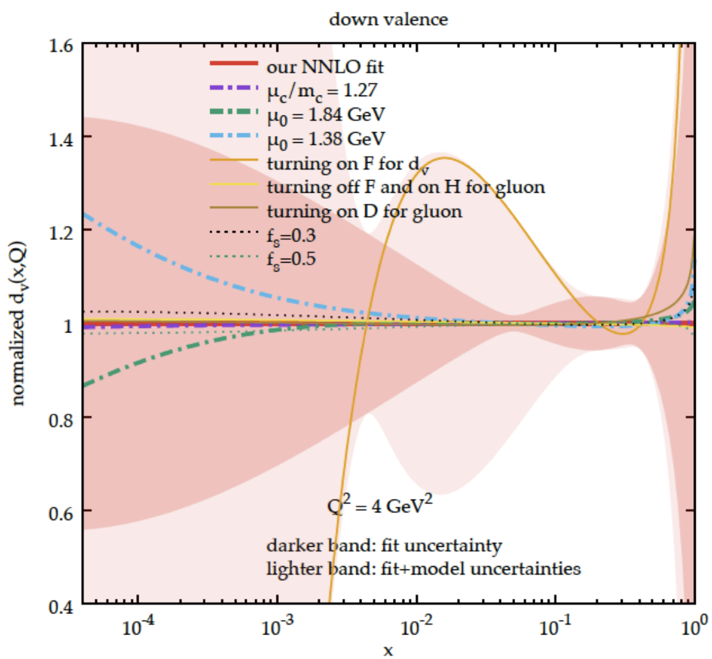
- Some differences are manifest (gluon/sea quarks)
- 1σ bands overlap or are very close to each other (apart from $\bar{d}+\bar{s}$)

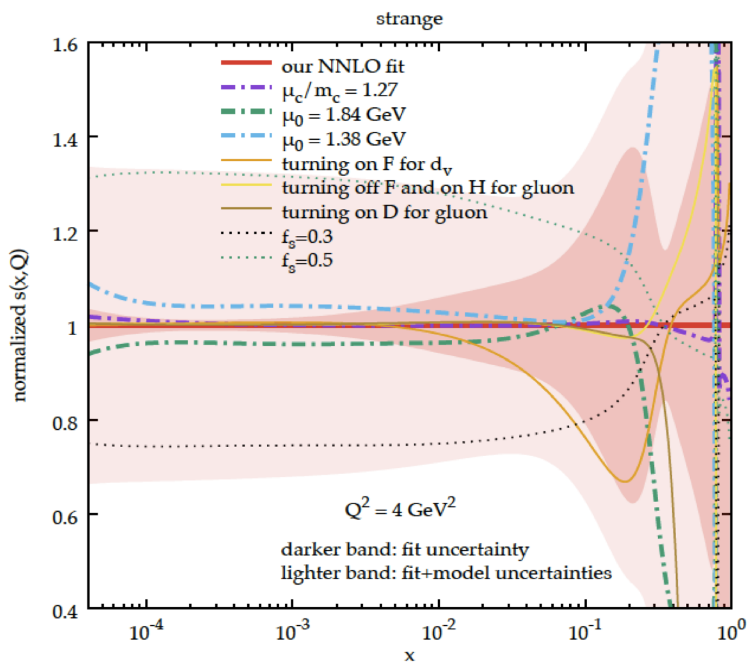
Stability of our fit

- We consider variations connected to the parametrization
- Variations of the fit scale:
  - μ_0 = 1.38 GeV and μ_c/m_c = 1.12 (μ_c = 1.46 GeV) – **Down variation**
  - μ_0 = 1.60 GeV and μ_c/m_c = 1.27 (μ_c = 1.85 GeV) – Intermediate step
  - μ_0 = 1.84 GeV and μ_c/m_c = 1.27 (μ_c = 1.85 GeV) – **Up variation**
- Strange fraction variations:
  - $f_s = 0.5$ (up variation) and $f_s = 0.3$ (down variation) – same as HERAPDF2.0
- Parametrization uncertainties addressed adding or removing parameters that do not change the fit quality. The ones giving the largest effect are:
  - Adding F_{d_v}
  - Adding D_g (more flexibility at large-x)
  - Adding H_g and removing F_g (possible effect at small-x)



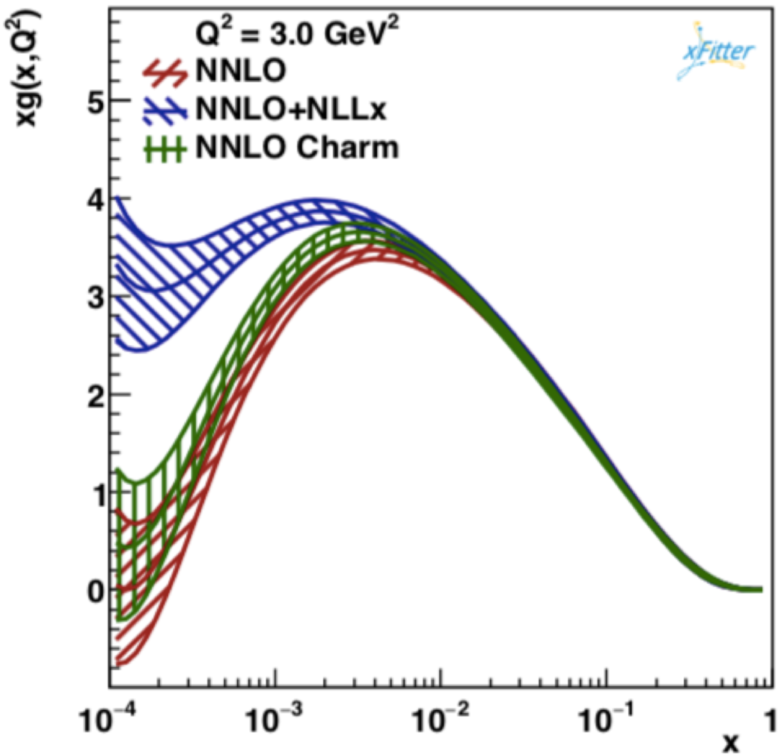
- The addition of the log term to d_v has the largest effect (negative for $x \lesssim 10^{-3}$)
- When D_g is activated, large-x shape changes substantially, but in a region where the gluon PDF is very small and largely unconstrained
- Effect of H_g (without F_g) very mild
- Up/down variations of f_s have a larger effect on the strange PDF (as expected)
- μ_0 variations have small effects

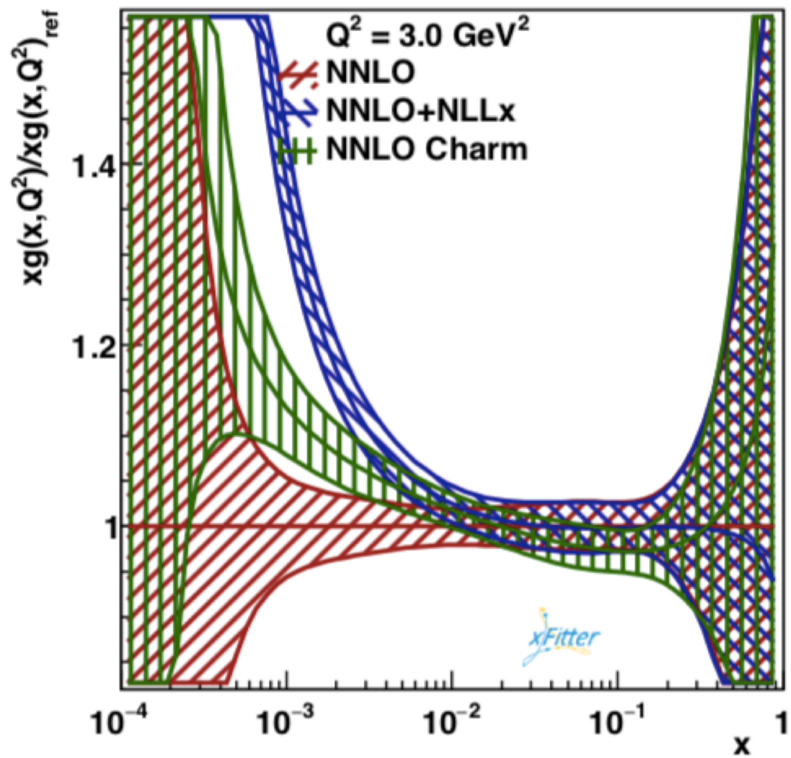




More sensitivity to the gluon PDF

- We also studied the inclusion of HERA Charm combined data (Eur.Phys.J. C78 (2018) no.6, 473)
- These data are directly sensitive to $xg(x,Q^2)$

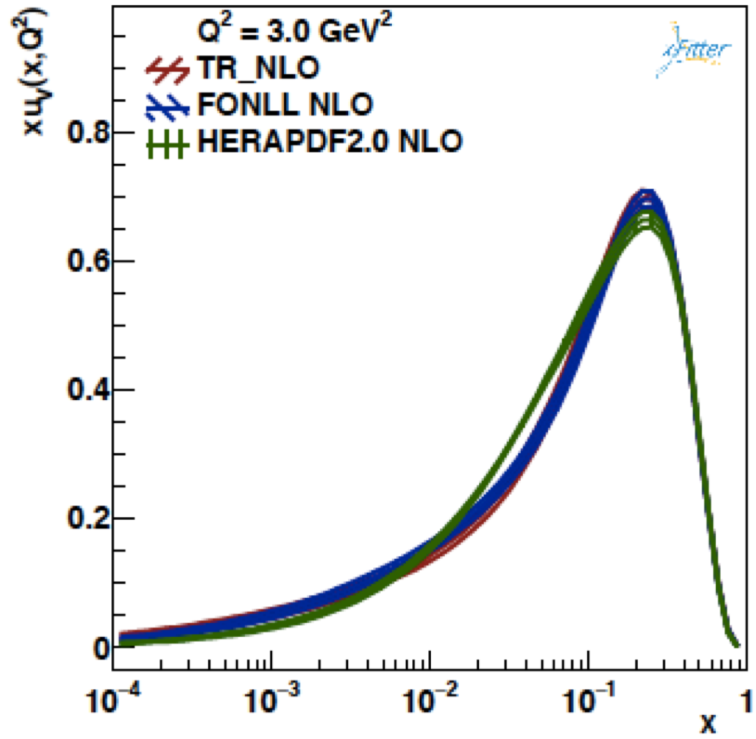


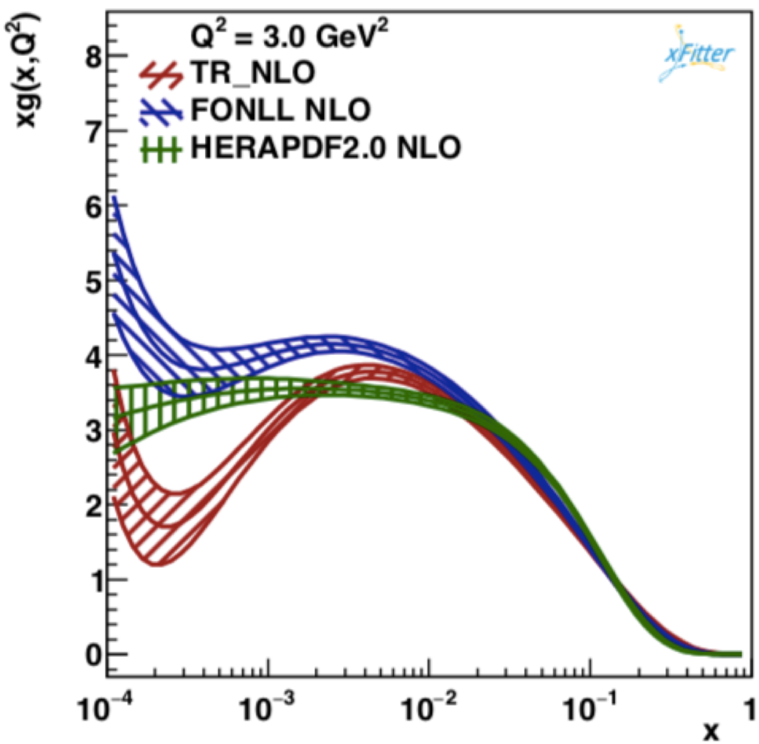


- It is remarkable that the two FO fits are in agreement within uncertainties

A NLO fit

- We also tried a NLO fit (using both TR and FONLL-B) – **preliminary**
- FONLL-B provides a better description than TR
- At low-x, same structure in the gluon PDF



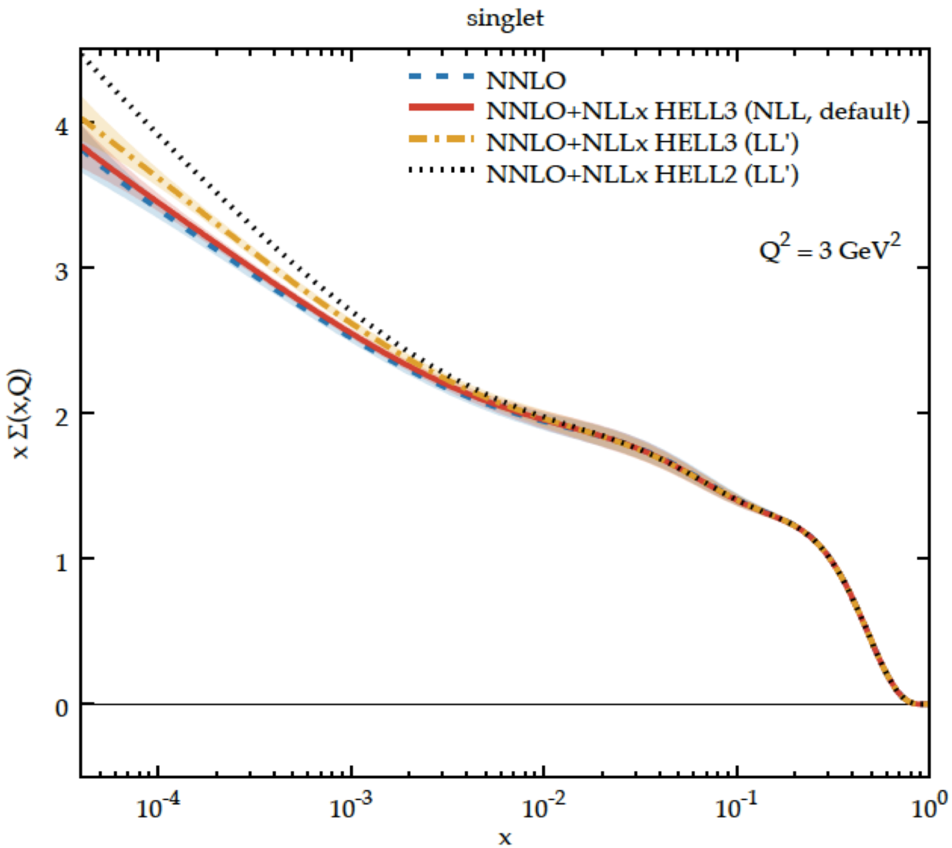


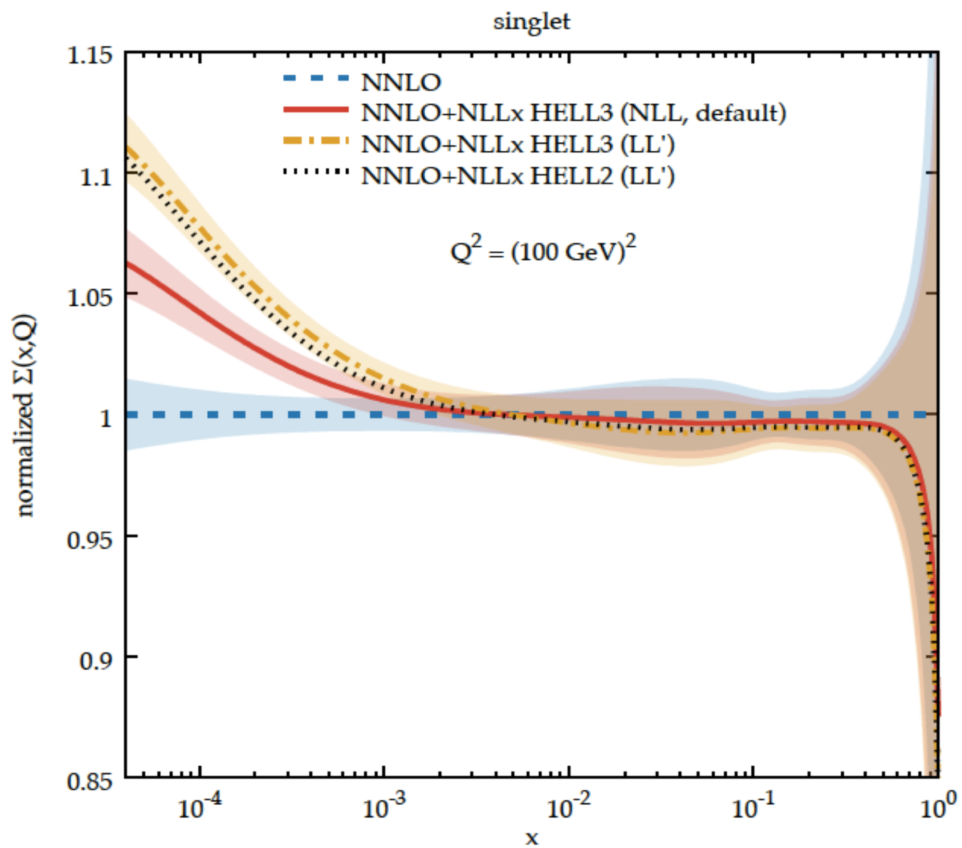
Dataset	TR NLO	FONLL NLO	HERAPDF2.0 NLO
HERA1+2 CCep	38 / 39	39 / 39	43 / 39
HERA1+2 CCem	49 / 42	48 / 42	54 / 42
HERA1+2 NCem	220 / 159	215 / 159	222 / 159
HERA1+2 NCep 820	72 / 70	68 / 70	68 / 70
HERA1+2 NCep 920	407 / 377	400 / 377	440 / 377
HERA1+2 NCep 460	223 / 204	225 / 204	217 / 204
HERA1+2 NCep 575	222 / 254	219 / 254	219 / 254
Correlated χ^2	76	67	86
Log penalty χ^2	-1.39	-6.17	+8.9
Total χ^2 / dof	1305 / 1127	1276 / 1127	1357 / 1145

Including small-x resummation

- The difference between two versions of HELL v3.0 is the introduction of a new default treatment of subleading logarithmic contributions

- These contributions may change the size of the effect resummation on the PDFs, but they remain rather different from their respective NNLO version





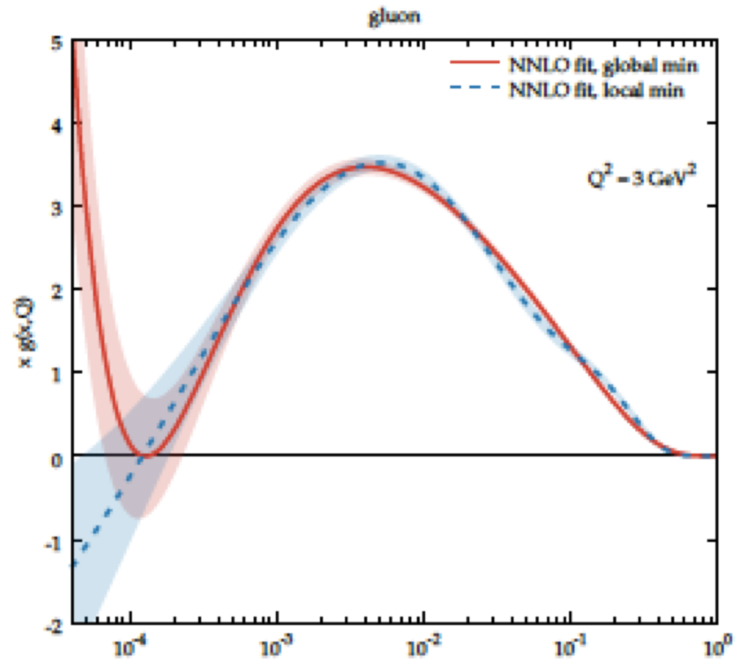
	B_g	C_g	F_g	G_g	B_{u_v}	C_{u_v}	E_{u_v}	F_{u_v}	G_{u_v}	B_{d_v}	C_{d_v}	$C_{\bar{u}}$	$D_{\bar{u}}$	$A_{\bar{d}}$	$B_{\bar{d}}$	$C_{\bar{d}}$	$D_{\bar{d}}$	$F_{\bar{d}}$
B_g	1.000	0.783	-0.508	-0.465	-0.055	0.055	0.074	-0.094	-0.098	0.000	-0.058	-0.176	0.043	-0.457	-0.525	-0.285		
C_g	0.783	1.000	-0.093	-0.070	-0.014	0.038	0.046	-0.100	-0.091	0.061	-0.061	-0.163	0.036	-0.352	-0.383	-0.345		
F_g	-0.508	-0.093	1.000	0.989	-0.072	0.117	0.142	-0.150	-0.119	0.051	0.063	0.011	-0.183	0.422	0.494	0.125		
G_g	-0.465	-0.070	0.989	1.000	-0.075	0.124	0.149	-0.157	-0.125	0.051	0.061	0.016	-0.218	0.488	0.558	0.110		
B_{u_v}	-0.055	-0.014	-0.072	-0.075	1.000	-0.202	-0.598	0.485	0.897	-0.226	-0.197	-0.127	-0.244	0.126	0.050	-0.634		
C_{u_v}	0.055	0.038	0.117	0.124	-0.202	1.000	0.846	-0.616	-0.381	-0.042	0.030	-0.535	-0.521	0.211	0.178	0.315		
E_{u_v}	0.074	0.046	0.142	0.149	-0.598	0.846	1.000	-0.871	-0.777	0.184	0.248	-0.462	-0.443	0.164	0.157	0.646		
F_{u_v}	-0.094	-0.100	-0.150	-0.157	0.485	-0.616	-0.871	1.000	0.806	-0.409	-0.445	0.356	0.523	-0.240	-0.206	-0.673		
G_{u_v}	-0.098	-0.091	-0.119	-0.125	0.897	-0.381	-0.777	0.806	1.000	-0.402	-0.384	0.002	0.048	-0.031	-0.064	-0.730		
B_{d_v}	0.000	0.061	0.051	0.051	-0.226	-0.042	0.184	-0.409	-0.402	1.000	0.940	0.390	0.133	0.075	0.069	0.383		
C_{d_v}	-0.058	-0.061	0.063	0.061	-0.197	0.030	0.248	-0.445	-0.384	0.940	1.000	0.262	0.013	0.123	0.112	0.437		
$C_{\bar{u}}$	-0.176	-0.163	0.011	0.016	-0.127	-0.535	-0.462	0.356	0.002	0.390	0.262	1.000	0.721	0.005	0.056	-0.126		
$D_{\bar{u}}$	0.043	0.036	-0.183	-0.218	-0.244	-0.521	-0.443	0.523	0.048	0.133	0.013	0.721	1.000	-0.595	-0.517	-0.083		
$A_{\bar{d}}$	-0.457	-0.352	0.422	0.488	0.126	0.211	0.164	-0.240	-0.031	0.075	0.123	0.005	-0.595	1.000	0.986	0.078		
$B_{\bar{d}}$	-0.525	-0.383	0.494	0.558	0.050	0.178	0.157	-0.206	-0.064	0.069	0.112	0.056	-0.517	0.986	1.000	0.122		
$C_{\bar{d}}$	-0.285	-0.345	0.125	0.110	-0.634	0.315	0.646	-0.673	-0.730	0.383	0.437	-0.126	-0.083	0.078	0.122	1.000		
$D_{\bar{d}}$	-0.042	0.022	0.029	-0.010	-0.665	0.241	0.571	-0.575	-0.706	0.188	0.215	-0.317	-0.048	-0.304	-0.252	0.752	1.000	
$F_{\bar{d}}$	0.562	0.363	-0.590	-0.652	0.013	-0.142	-0.142	0.166	0.086	-0.061	-0.095	-0.094	0.429	-0.941	-0.983	-0.147	0.200	1.000

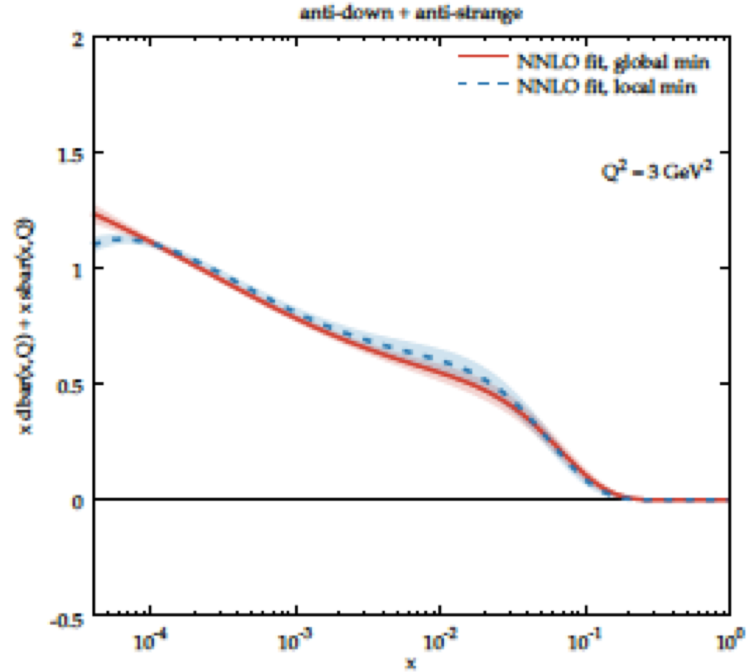
- Correlation matrix between fit parameters
- Most of them are poorly correlated
- When present, F and G parameters strongly correlated (they probe the same x regime)
- They are also correlated to B parameters (same reason as above)
- Down-valence parameters highly correlated (same as for HERAPDF2.0)

Local minima

- While fitting data with fixed-order theory, we found a local minimum pretty far away from the global minimum presented in the paper
- Main difference in the gluon PDF: global minimum with $B_g < 0$, while local minimum with $B_g > 0$
- The fit converged in the local minimum has an extra parameter in it: cubic logarithmic term in the gluon PDF (H_g)
- Even though very significant differences in some parameters, χ^2 really similar
- When transitioning from one minimum to the other in the parameter space, the χ^2 becomes much larger → with a standard minimization routine it is highly unlikely that once the local minimum is found, it could converge to the global minimum
- The physical expectation $B_g < 0$ was crucial to guide us

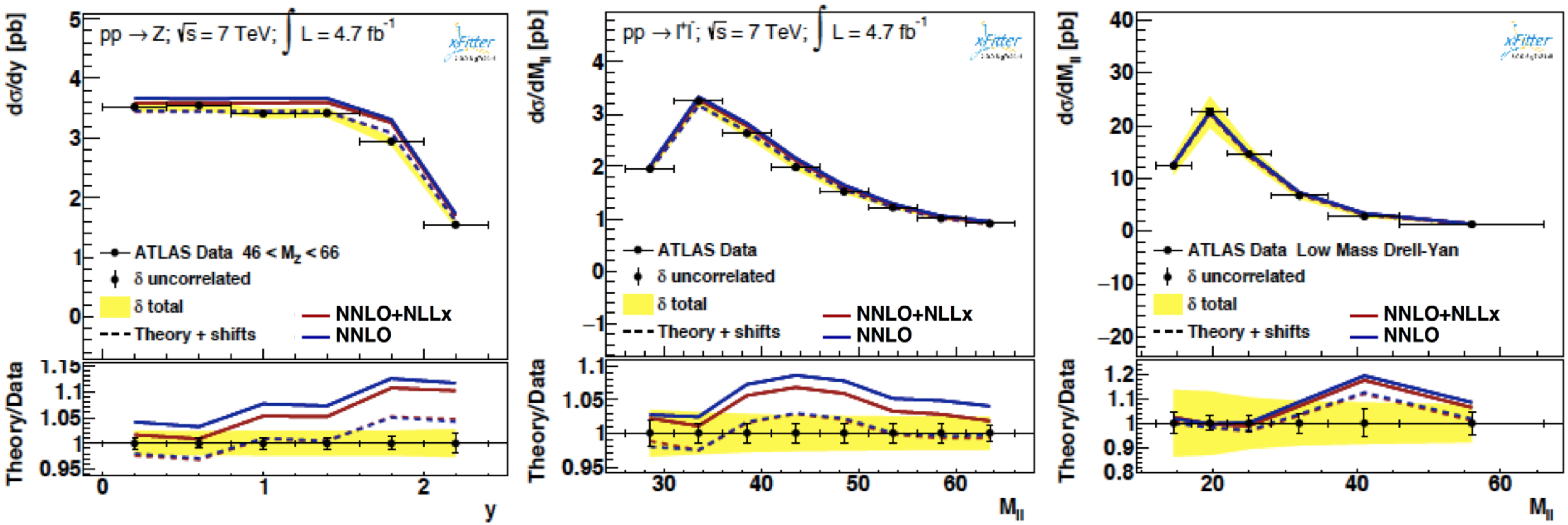
Fitted parameter	NNLO (FONLL) local minimum	NNLO (FONLL) global minimum	NNLO+NLLx HELL 3.0 (NLL)
B_g	0.34 ± 0.07	-0.55 ± 0.03	-0.52 ± 0.04
C_g	8.8 ± 1.0	4.5 ± 0.5	4.5 ± 0.5
F_g	0.76 ± 0.04	0.230 ± 0.003	0.217 ± 0.005
G_g	0.22 ± 0.02	0.0131 ± 0.0004	0.0112 ± 0.0005
H_g	0.017 ± 0.002		
B_{u_v}	0.85 ± 0.06	0.83 ± 0.06	0.76 ± 0.06
C_{u_v}	4.5 ± 0.1	4.6 ± 0.2	4.6 ± 0.1
E_{u_v}	1.7 ± 0.8	1.9 ± 1.0	2.6 ± 1.1
F_{u_v}	0.38 ± 0.04	0.37 ± 0.05	0.35 ± 0.04
G_{u_v}	0.062 ± 0.011	0.058 ± 0.012	0.049 ± 0.010
B_{d_v}	1.01 ± 0.09	0.98 ± 0.10	0.99 ± 0.09
C_{d_v}	4.7 ± 0.4	4.7 ± 0.5	4.7 ± 0.5
$A_{\bar{d}}$	0.070 ± 0.008	0.13 ± 0.02	0.14 ± 0.02
$B_{\bar{d}}$	-0.45 ± 0.02	-0.34 ± 0.02	-0.33 ± 0.02
$C_{\bar{d}}$	28 ± 3	24 ± 2	24 ± 3
$D_{\bar{d}}$	76 ± 17	40 ± 12	38 ± 10
$F_{\bar{d}}$	0.084 ± 0.001	0.072 ± 0.004	0.071 ± 0.004
$C_{\bar{u}}$	11 ± 1	11 ± 1	11 ± 1
$D_{\bar{u}}$	33 ± 6	20 ± 4	18 ± 4
χ^2/d.o.f.	1314/1126	1312/1127	1284/1127





First look at low-mass DY ATLAS data and low-mass Z sideband @7 TeV

- First look at the description of the following data samples:
  - **JHEP 06 (2014) 112** – low-mass DY, 1.6 fb^{-1}
  - **EPJC 77 (2017) 6 367** – W,Z precision measurement, 4.7 fb^{-1}



	NNLO+NLLx	NNLO
ATLAS low mass DY 2011	9.5 / 8	11 / 8
ATLAS DY mass 2010 extended data	6.4 / 6	6.9 / 6
ATLAS low mass Z rapidity 2011	31 / 6	31 / 6